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Compressed air energy storage systems: Components and operating parameters – A review

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ABSTRACT

Energy storage systems are a fundamental part of any efficient energy scheme. Because of this, different storage techniques may be adopted, depending on both the type of source and the characteristics of the source. In this investigation, present contribution highlights current developments on compressed air storage systems (CAES). The investigation explores both the operational mode of the system, and the health & safety issues regarding the storage systems for energy. The investigation also includes a detailed conclusion, which summarises the vast significance of novel energy storage technology. The investigation thoroughly evaluates the various types of compressed air energy storage systems, along with the advantages and disadvantages of each type. Different expanders ideal for various different compressed air energy storage systems are also analysed. Design of salt caverns and other underground and above compressed air storage systems were also discussed in terms of advantages and disadvantages.

1. Introduction

The world is currently exploring new methods for generating energy, instead of relying on fossil fuels [1]. Primarily due to the devastating effects the burning fossil fuels has on the environment, but also considering the fact that fossil fuels are rapidly depleting. Other factors regarding price of fossil fuels being unstable are also key contributing factors that necessitate a need for alternative sources of energy generation. The high demand for energy is directly proportional to worldwide population growth, industrialization as well as technological advancement [[2],[3]]. A closer look at global energy consumption in 2019 reveals that primary energy consumption increased by 2.9% [1]. This year also witnessed more than a 2% increase in carbon emissions as directly related to electricity generation and the automotive industry. This increase is the highest in the past decade, as the maximum increase in carbon emissions prior was 0.6 CO_2Gt [2]. Since most reliable and common way of energy production always involve fossil fuels oil, energy production, especially as electricity, contributes to one third of total fuel needed worldwide (32%). For example, coal accounts for 26% of total world energy supply that will be converted to electricity, whereas gas contributes to 23% to fuel used annually and biomass contributes 10%.. Biomass, as well as electricity can be divided into hydroelectricity, nuclear and renewables. Analysis of data compiled from 2000 to 2019, shows an increase in various types of energy generation sources, with the exception of only renewables. Energy efficiency has also increased, even though this increase was marginal. In 2015, the industrial sector was the sector that consumed the most energy in comparison to others. Most of this energy was used for manufacturing purposes. Fig. 1 shows a deviating conclusion in 2017, where the transport sector was the one that has grown the most in energy demand.

Climate change due to depletion of the ozone layer can be attributed to the high dependency on fossil fuels. Renewable energy is considered the pragmatic approach in reducing this dependency [4]. This is merely because these sources of energy are both abundant and environmentally friendly. Despite obvious advantages of these energy generation mediums, there are still challenges facing their wide scale adaptation, such as intermittency in energy supply at certain times. This and other issues are considered crucial in the renewable energy generation sector, as they

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determine not only the performance of the system, but also cost.

An everyday example was noted in 2014, where power from renewable sources accounted for 58.5% power capacity generated in that year. By December 2014, 27.7% of global power produced was from renewables as they ended up supplying 22.8% of worldwide electricity [4]. As previously noted, intermittency reduces power produced and increases uncertainty. This raises the importance of provisions to store energy when the supply is available, but demand is weak. Adopting this strategy will enhance system performance and system cost will also fall [5], thereby justifying the necessity of storage systems in any renewable source of power generation. Fig. 2 shows different energy storage systems that have been introduced over the past decades.

Table 1 explains performance evaluation in some energy storage systems. From the table, it can be deduced that mechanical storage shows higher lifespan. Its rating in terms of power is also higher. The only downside of this type of energy storage system is the high capital cost involved with buying and installing the main components. The characteristics exhibited by mechanical energy storage systems makes them ideal for load levelling as well as storage [7].

A technology already considered as being mature is pumped hydro-energy storage. There are currently numerous pumped hydro-energy storage system pilot projects in place as they are considered the “largest storage battery known”. The main limitation of this energy storage system is due to geographical restrictions. This energy storage medium requires damming of water bodies, which requires extra initial capital during the development of such projects [15]. Pumped hydro as a form of energy storage has therefore, been hindered in some parts of the world, due to these outstanding factors [16].

Another idea is compressed air energy storage (CAES) that stores energy by pressurizing air into special containers or reservoirs during low demand/high supply cycles, and expanding it in air turbines coupled with electrical generators when the demand peaks The storage cavern can also requires availability be a suitable geographical site such as a depleted oil/gas well or a salt mine. The number of sites available for compressed air energy storage is higher compared to those of pumped hydro [[17],[18]]. Porous rocks and cavern reservoirs are also ideal storage sites for CAES. Gas storage locations are capable of being used as sites for storage of compressed air [18]. Today, several research activities are being carried out to explore the application of CAES on small scale projects, following their successful integration on large scale renewable energy systems [19–22]. Small-scale CAES systems are gradually becoming a possible replacement for batteries, super capacitors etc. Small-scale CAES have several advantages- including longer lifespan, lower number of maintenances required, and the ability to perform better even in worse environmental conditions. Investigations conducted on CAES systems have often been limited to the historical predecessors of this energy storage medium, and classification of this storage technology [21–25]. Ideal methods for selecting components of compressed air energy storage systems have not been discussed thoroughly in an article to date. This article aims to bridge that gap in literature and steadily define the criteria for selecting components for CAES systems. To understand the importance of CAES systems, Table 2 compares the environmental effects of different energy storage systems.

One crucial component in CAES systems that contributes to the power output, as well as performance of the system, is the expander, or air tubrine. The operation of the system, along with the power that can be exerted from the storage system determines the appropriate type of expander necessary for the system [33]. Expanders for compressed air energy storage are categorised into two types. These are displacement and dynamic types, as shown in Fig. 3 below.

Thorough investigation of the organic Rankine cycle has exposed ways of choosing vane expansion machines ideal for CAES systems. Investigations on ways of choosing various expansion machines have also been carried out in literature [34]. Many researchers discussed the operational characteristics necessary when choosing the correct expanders for efficient organic Rankine cycle systems [35]. Using several working fluids, a group of researchers compared various expansion machines (reciprocating, screw and scroll expanders) [36–40].

2. Overview of compressed air energy storage

Compressed air energy storage (CAES) is the use of compressed air to store energy for use at a later time when required [41–45]. Excess energy generated from renewable energy sources when demand is low can be stored with the application of this technology. Compressed air energy storage systems may be efficient in storing unused energy, but large-scale applications have greater heat losses because the compression of air creates heat, meaning expansion is used to ensure the heat is

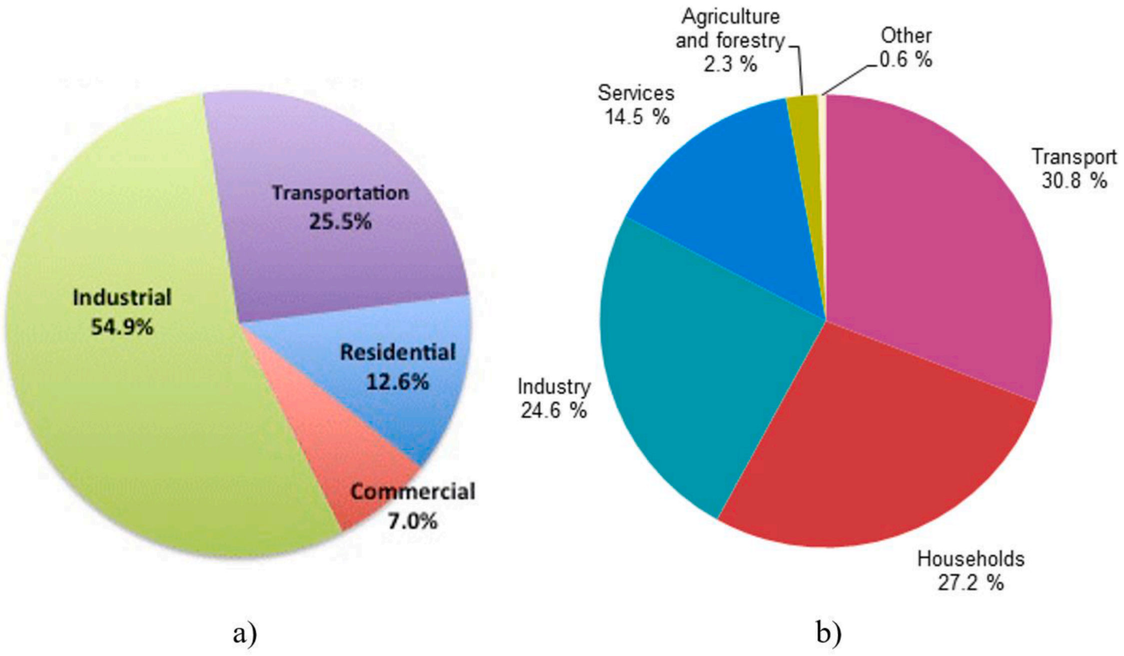

Fig. 1. Energy consumption by sector in 2015 (a) vs 2017 (b) [2].

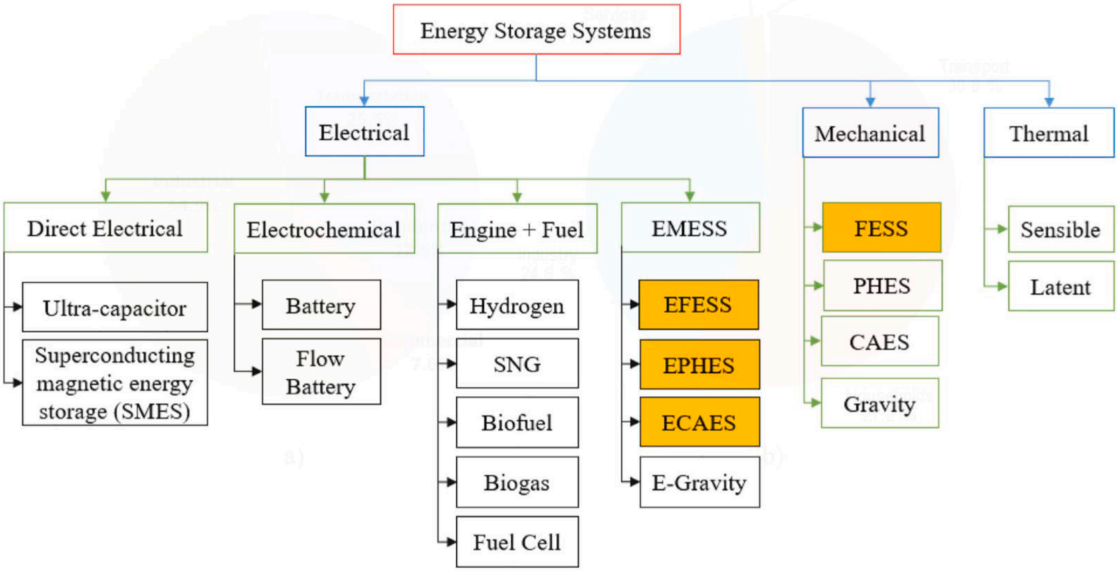

Fig. 2. Energy storage system classifications, the orange marked types are the most commonly used mechanical energy storage systems. [6].

Table 1
Energy storage system characteristics.

Energy storage system	Power density(W/L)	Energy density(Wh/L)	Power rating (MW)	Energy capacity (MWh)	Efficiency %	Lifetime/yr	Ref
LS Compressed air energy storage system	0.5 –2	1 - 6	100 - 1000	Less than 1000	40 - 70	20 - 40	[8]
SS Compressed air energy storage system	More than 2	Greater than 6	0.003 – 10	Less than 0.1	65	More than 23	[9]
Pumped hydro energy storage	0.45 – 1.5	0.5 – 2	100 – 5000	500 - 8000	70 – 85	40 - 60	[10]
Lithium ion battery	1000 – 10,000	100 – 500	1 – 100	0 - 10	75 - 97	4- 20	[11]
Lead acid battery	1 - 500	40 - 90	0 - 40	1- 40	63 - 90	5- 15	[12]
Supercapacitor	More than 100,000	10 - 30	0 – 0.3	0 – 0.0005	84 - 95	10 – 30	[13]
Fuel cell	More than 500	500 – 3000	Less than 50	0.312	20 - 66	5 – 20	[14]

Table 2
Storage devices and their effect on the environment.

Storage medium	Effect on the environment	Ref
Synthetic natural gas	Toxic emissions into atmosphere	[26]
Biofuel	Quality of water challenges	[27]
Biogas	Release of methane	[28]
Mechanical storage medium	Lesser effect on the environment	[29]
Supercapacitors	Carbon issues	[30]
thermochemical	dependant on reactant as well as product	[31]
thermal energy storage	dependant on the material	[32]
Batteries	Heavy metal pollution	[33]

removed [[46],[47]]. Expansion entails a change in the shape of the material due to a change in temperature. The heat generated during compression can also be stored and used later during the expansion (discharge) stage, which further improves the storage efficiency, as the same amount of heat stored is used later [48]. The compressors- one of the key components of compressed air energy storage systems operate using prime movers, such as motors [[49],[50]]. These compressors pressurize air as it starts its journey into the storage cavern [51]. The motors required for driving the compressors can also be powered using energy from renewable sources such as photovoltaics or wind turbines [[52],[53]]. Heat exchangers are coupled to these compressors to extract and store thermal energy [54–56]. This is useful during the discharge phase as air is heated using heat exchangers with the same heat that has been extracted [[57],[58]]. The expanders, or air turbines are important as they produce work, which is transformed into electricity by coupling them to generators [59–61]. The energy conversion in a CAES system can be summarized into five main stages. The first stage is air compression with simultaneous extraction of heat during charging, followed by storage the later, when the time of discharge comes, the air is routed to the expanders via the heat exchangers to be heated up and generate work. Later stages involve electricity generation via electrical generators coupled to the air turbines, as shown in Fig. 4.

CAES systems are categorised into large-scale compressed air energy storage systems and small-scale CAES. The large-scale is capable of producing more than 100MW, while the small-scale only produce less than 10 kW [60]. The small-scale produces energy between 10 kW - 100MW [61]. Large-scale CAES systems are designed for grid applications during load shifting [62]. For an uninterrupted supply of power, the small-scales are often ideal, especially for renewable energy sources. Large scale CAES systems usually depend on the availability of an accessible and impermeable cavern for air storage and pressurization. Whenever such cavern is not available, air can be stored in modular canisters under a pressure which the canister material can withstand. Alami et al. has investigated such a modular system that consist of three 7 litre cylinders connected together and discharging into an air turbine. The operational pressure of the system was kept below 5 bar (trials on 3, 4 and 5 bar are reported) in order to avoid any thermal or expansion losses, and to set the benchmark for the experimental system. The reported overall system efficiency was ~97%, with a mechanical efficiency (converting from compressed air to the power output in the air turbine) of ~95%. The same group replaced air with carbon dioxide in a closed-loop system, and obtained efficiencies of 79% at lower operating pressures (maximum 3 bar) due to the higher density of carbon dioxide.

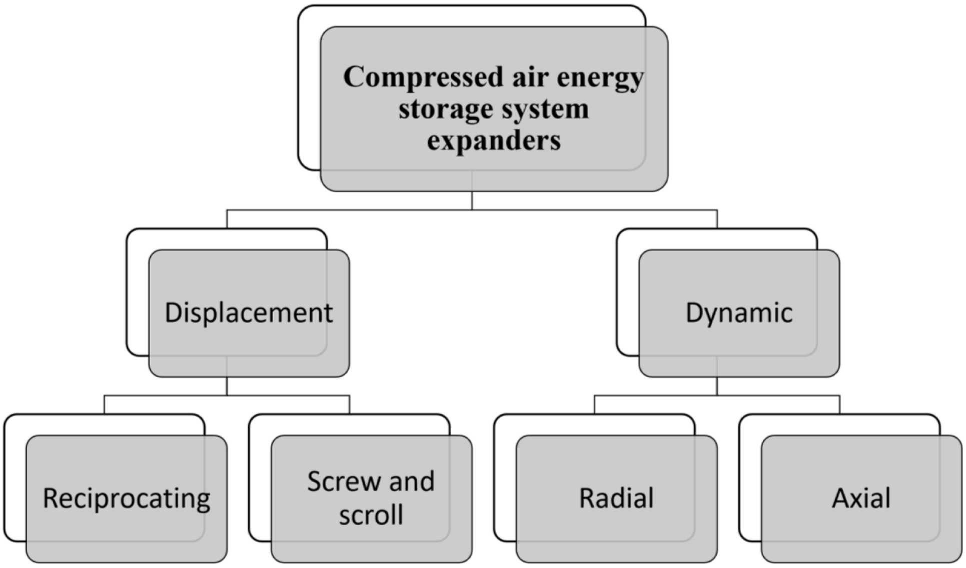

Fig. 3. Various categories of CAES expanders.

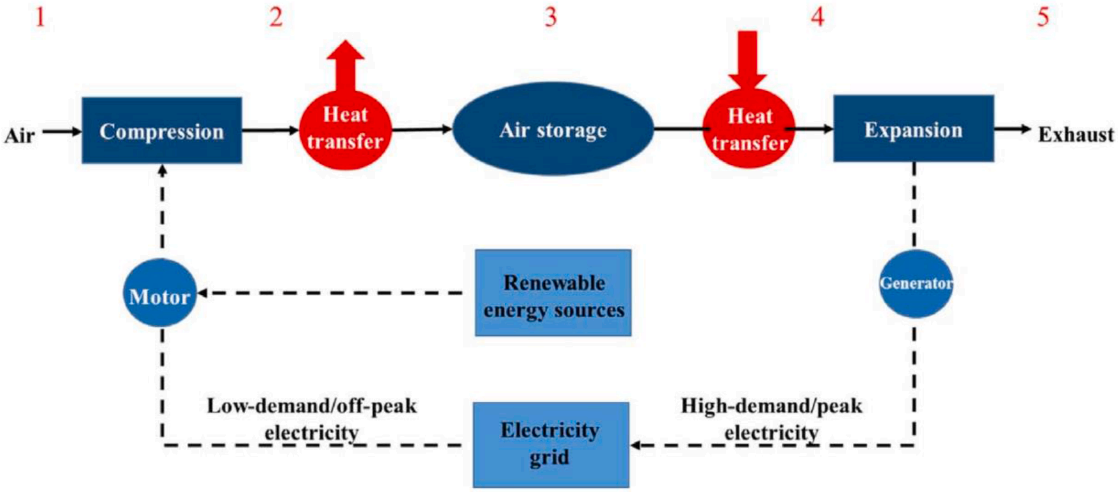

Fig. 4. Operational stages of CAES.

Research into integration of small-scale compressed air on renewable energy systems has also been investigated in literature [62]. The literature explored ways of reducing the compressed work. Micro-scale compressed air energy systems are also ideal for multipurpose systems. Micro-scale compressed air energy storage systems integrated to renewable energy systems were also investigated to ascertain the air cycle heating, as well as the cooling [63]. Expansion machines are designed for various compressed air energy storage systems and operations. An efficient compressed air storage system will only be materialised when the appropriate expanders and compressors are chosen. The performance of compressed air energy storage systems is centred round the efficiency of the compressors and expanders. It is also important to

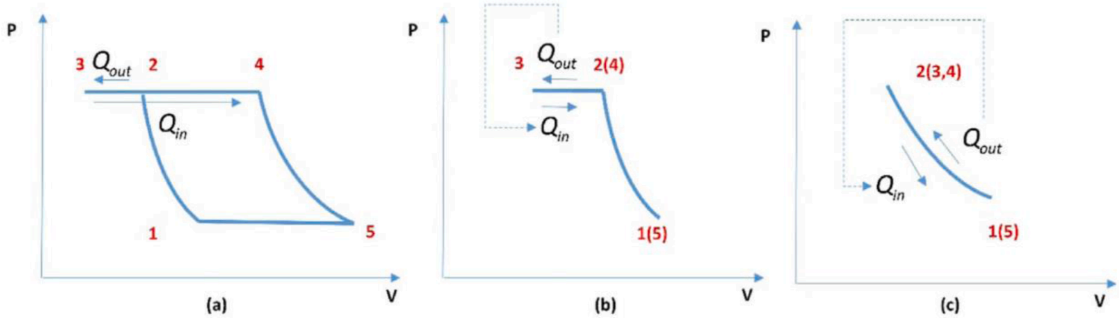

Fig. 5. Pressure volume diagram for CAES system (a) Diabatic (b) Adiabatic (c) Isothermal [65].

determine the losses in the system as energy transfer occurs on these components. There are several compression and expansion stages: from the charging, to the discharging phases of the storage system. Research has shown that isentropic efficiency for compressors as well as expanders are key determinants of the overall characteristics and efficiency of compressed air energy storage systems [64]. Compressed air energy storage systems are sub divided into three categories: diabatic CAES systems, adiabatic CAES systems and isothermal CAES systems. Fig. 5 shows the various types of CAES systems' operational characteristics.

Fig. 6, 7 present the operational characteristics of adiabatic CAES [72], and the Renewable source of energy and Adiabatic CAES system [77] respectively.

2.1. Operational principles of compressed air energy storage (CAES)

The method of operation for CAES systems is quite straightforward [66]. Compressors powered by electricity are used to charge the storage, and this transforms electrical energy into potential energy- commonly referred to as exergy. The environment is generally considered as a low-pressure reservoir, making the use of air as the main driver for this technology feasible [67]. The air, which is pressurized, is kept in volumes, and when demand of electricity is high, the pressurized air is used to run turbines to produce electricity [68]. There are three main types used to deal with heat in compressed air energy storage system [271]. These are:

- Adiabatic
- Diabatic
- Isothermal

2.1.1. Adiabatic

Adiabatic CAES systems are designed for storage of heat during the compression stage [69–71]. These energy storage systems are designed using thermal energy storage devices. There are instances however, where these storage devices are not needed.

Adiabatic CAES with thermal energy storage systems is designed for the recovery and storage of heat. This stored heat is later utilised during expansion [73]. Adiabatic CAES with thermal energy storage is designed to solve the limitations of adiabatic CAES, without resorting to thermal energy storage. Elimination of heat from the air stream leads to higher final pressures, resulting in higher energy densities [74]. Adiabatic CAES without thermal energy storage use temperature generated from the compressed air and hot air is then kept in an enclosure. The limitation of this type of storage system has to do with the storage volume being temperature resistant. This phenomenon occurs because at a lower pressure ratio, the air temperature remains higher. The temperature of the compressed air is usually greater than 250 °C at a pressure of 10 bar. Adiabatic compressed air energy storage without thermal energy storage tends to have lower storage pressure, hence the reduced energy density compared to that of thermal energy storage [75]. The input energy for adiabatic CAES systems is obtained from a renewable source. The overall efficiency of the adiabatic compressed air energy storage system is determined by the round-trip efficiency. This is simply the output power obtained during discharge, to the input power needed during charging. The off-peak electricity is kept as compressed air, as well as heat kept in thermal energy storage for adiabatic CAES. The energy conversion as well as the storage determines the efficiency of adiabatic CAES. These storage systems usually have efficiencies between 65 and 75% [76]. These projected efficiencies have not been practically confirmed to date. The efficiency of adiabatic CAES systems tends to vary based on different designs. Efficiency of a 16,500 MJ adiabatic CAES system with a different configuration established an efficiency of 72% [77]. Today, many investigations are being conducted using adiabatic CAES, with other renewable energy sources as well as efficiency of such systems being pegged at 46%.

The efficiency of an adiabatic CAES system was enhanced by recovering the loss in pressure. This investigation saw an increment in output power from 31.10 to 32.81 megawatts, while efficiency soared from 61.95% - 65.36% [78]. Other researchers also explored the integration of a photovoltaic power system on an adiabatic CAES system [79]. A further discussion into the ADELE project will be carried out in later investigations. Another 1.5MW adiabatic CAES project has also been executed in China [80]. The efficiency, along with the pressure loss for heat exchangers in adiabatic CAES systems has also been researched and concluded that an increase in the efficiency of the heat exchangers has an impact on the overall efficiency of the adiabatic CAES system [81]. It has also been stated in literature that the creation of high temperature thermal storage, made of a compressor of whose materials are temperature resistant, are ideal for the enhancement of the efficiency of adiabatic CAES systems [82]. More than 70% efficiency (from literature) was also obtained when thermal energy storage was also integrated in adiabatic CAES systems [83]. With the use of a radial compressor, an adiabatic compressed air storage system operating at a lower temperature was also investigated. The temperature for the hot thermal energy storage system was noted to be between 95 and 200 °C [84]. For this investigation, it was observed that the efficiency of the adiabatic compressed air energy storage system was between 52 and 60%, a number that was less than expected. Despite this deviation, several advantages were also noticed. The first is the fact that they exhibited quick start up traits, as well as broad range of partial load characteristics [85]. Another investigation that was carried out on a low temperature adiabatic energy storage system obtained a cycle efficiency of 68%, and a heat energy

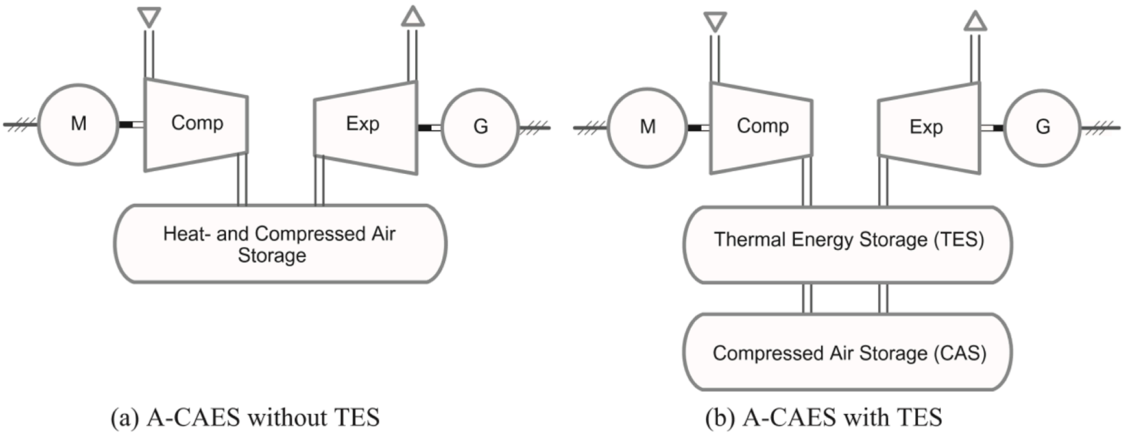

Fig. 6. Operational characteristics of adiabatic CAES [72].

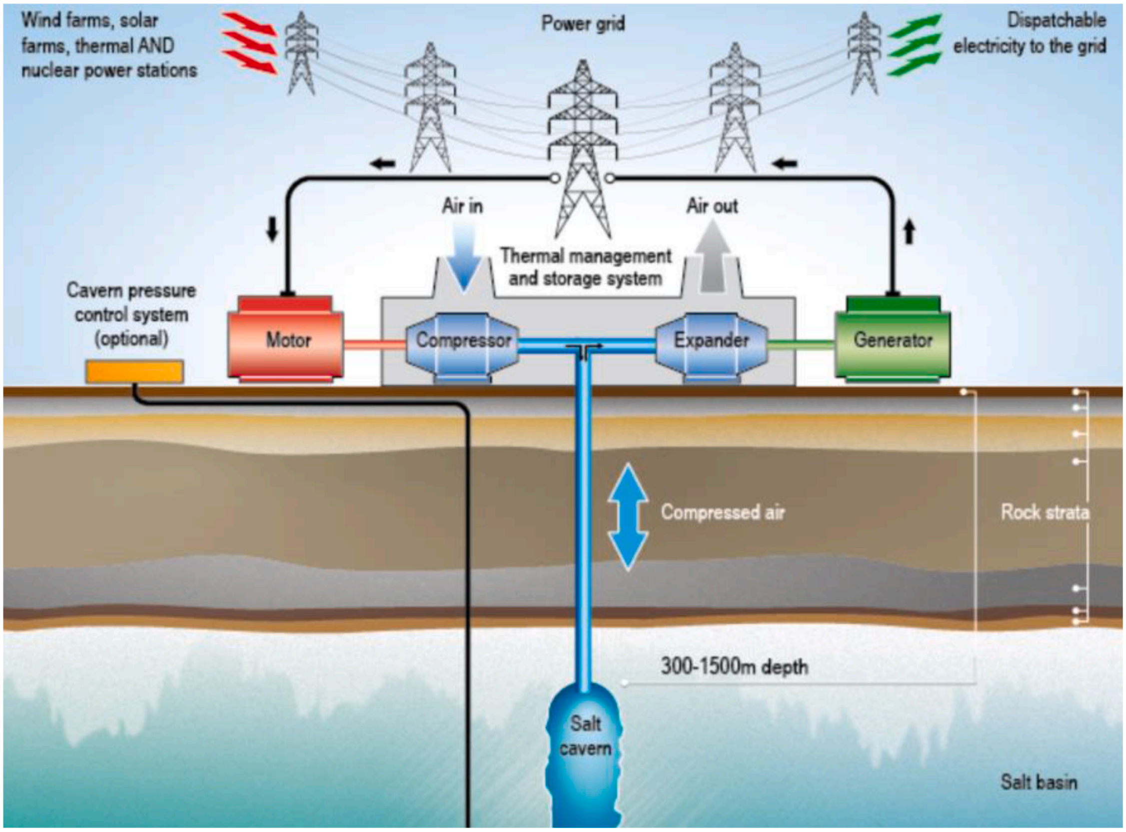

Fig. 7. Renewable source of energy and Adiabatic CAES system [77].

efficiency of 60% [86–91]. It can therefore be concluded that the critical factor that determines the efficiency of adiabatic CAES systems is temperature, as shown in Fig. 8. This subsequently determines the overall efficiency of the entire storage plants. On the other hand, cycle efficiency is not dependant on storage temperature. The reduction in cycle efficiency at lower storage temperatures is marginal, and this occurs due to exergy losses from various heat exchange processes.

Thermal energy storage integrated to an adiabatic CAES system is usually categorised into high temperature, medium and low temperature processes. The storage temperature for the high temperature process usually exceeds 400 °C. Medium temperature's is usually between 200 °C and 400 °C, while the lower temperature process is usually lower than 200 °C [92].

2.1.1.1. *High temperature operation.*

One way of enhancing the exergy storage capacity per unit mass of air for adiabatic compressed air energy storage system is by preheating the air prior to compression, as depicted in Fig. 9. The specific volume of the air increases due to an increase in air temperature before the compression stage. This causes an increase in the work requirement for the compressors. A storage system with these

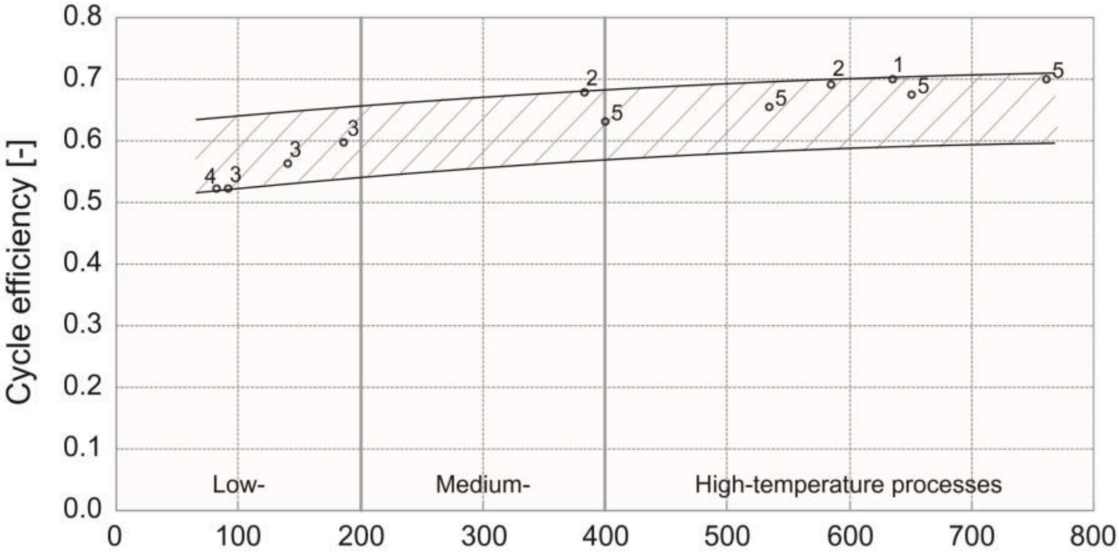

Fig. 8. Adiabatic compressed air energy storage cycle efficiency with respect to storage temperature [92].

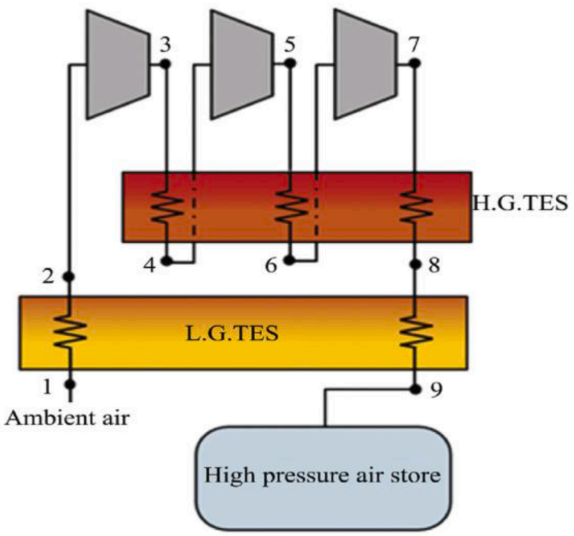

Fig. 9. High temperature CAES operated adiabatically [93].

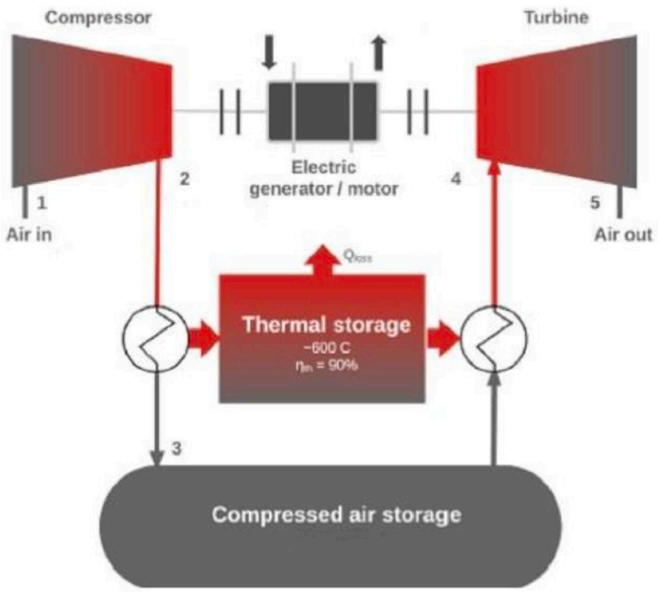

Fig. 11. High temperature advanced CAES operated adiabatically [94].

characteristics is described as a high temperature adiabatic CAES system.

It can be observed from Fig. 10 that when charging, the air is heated first between points 1–2, prior to compression. This is common for lower grade thermal energy storage. For a higher-grade thermal energy storage system, the heat of compression is maintained after every compression, and this is denoted between point 3–4, 5–6 and 7–8. The main exergy storage system is the high-grade thermal energy storage. The reset of the air is kept in the low-grade thermal energy storage, which is between points 8 and 9. This stage is carried out to produce pressurized air at ambient temperature captured at point 9. The air is then stored in high-pressure storage (HPS). Fig. 11 depicts the temperature and pressures changes of the air stream at various points in the system, depicted in Fig. 10.

For the advanced adiabatic compressed air energy storage system depicted in Fig. 11, compression of air is done at a pressure of 2.4 bars, followed by rapid cooling. There is considerable waste of heat caused by the exergy of the compressed air. This occurs due to two factors.

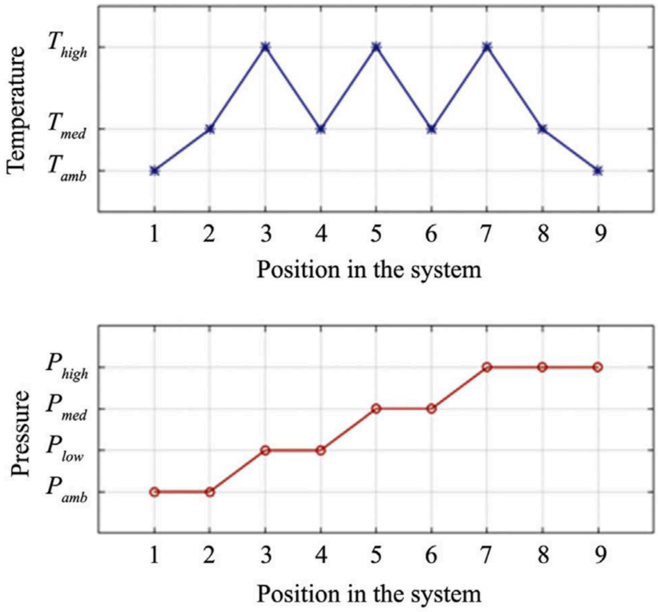

Fig. 10. Air stream pressure and temperature at various positions in the system [94].

There is also a reduction in compression work due to inter-cooling as this work is divided between two compressors thereby increasing cycle efficiency. In the absence of inter-cooling, the temperature of the air at the outlet would be higher than ambient temperature, because of irreversible damage to the applied turbo machinery. The exergy loss is unavoidable but to mitigate this challenge, the temperature relating to the part for the exergy after the initial compression can be dumped. The next compression leading to the final pressure of 65 bars can be done in the absence of any additional cooling. Carrying out this step results in an outlet temperature of 580 °C. The air that is pressurized flows through the thermal energy storage system. The temperature relating to the exergy of the air is made to flow through a solid thermal storage media. There is conditioning of the air after this stage with the aid of an extra cooler. The air is then stored under a specific temperature and pressure. The discharge phase leads to the flow of air via the same thermal energy storage device but in an opposite direction. The air is then raised up to temperatures beyond 550 °C. The air is then expanded to ambient pressure with the aid of a generator paired with a turbine, shown in Fig. 12. The subsequent sections will discuss the medium and lower temperature operating conditions.

2.1.1.2. Medium temperature operation. Investigations into 2 stage thermal energy storage systems have also been investigated at lower temperatures [[96],[97]]. The process temperature can also be made to be under than 400 °C, due to the transfer of temperature dependant region of the exergy for the compressed air to the thermal energy storage device twice. The cycle efficiency in this case tends to be very low, but this is accounted for by compressor technology, as well as thermal energy storage mediums [96]. These characteristics are considered advantageous for these types of energy storage mediums, hence why today several research investigations are being conducted to explore this energy storage technology further [98]. The main limitation for this technology has to do with the start up, which is currently between 10 and 15 min because of the thermal stress being high. The air is first compressed to 2.4 bars during the first stage of compression. Medium temperature adiabatic compressed air energy storage system depicted in Fig. 13.

There is further compression to a pressure of 19 bars in the second step, as shown in Fig. 14. The air then exists the second stage at temperatures around 380 °C. There is cooling of the air as it flows via the

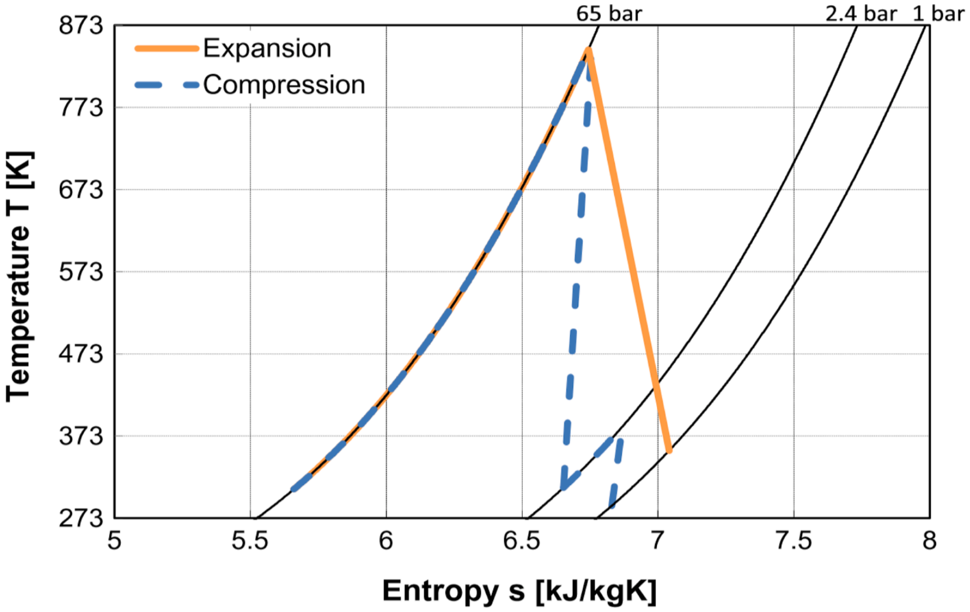

Fig. 12. T, S diagram of high temperature adiabatic compressed air energy storage [95].

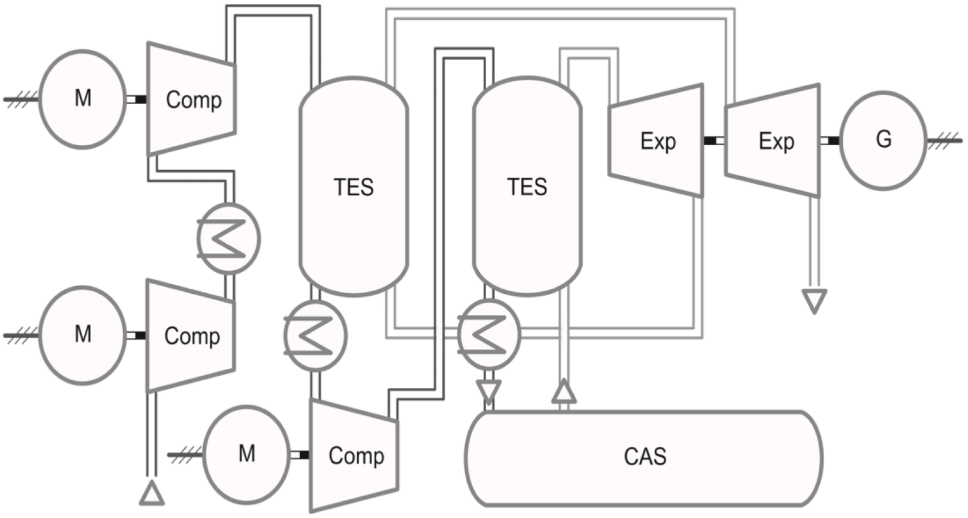

Fig. 13. Medium temperature adiabatic compressed air energy storage [41].

thermal energy storage device, followed by an after-cooler. From this stage, there is compression of the air until required pressure is achieved. This means that the temperature of the air is again raised to 380 °C. There is an exchange of heat in the second thermal energy storage system. During the discharge stage, there is an expansion stage, followed by preheating using the 2 thermal energy storage devices.

2.1.1.3. Low temperature operation. In the last decade, many research activities have been conducted to explore storage temperatures below 200 °C [99]. The use of a liquid thermal energy storage medium tends to be the most advantageous of the low-temperature adiabatic compressed air energy storage systems. These liquid thermal energy storage medias support the application of heat exchangers, as well as compression and expansion devices. In order to achieve a lower storage temperature but a higher energy density, there must be transfer of heat for each stage of the process, as depicted in Fig. 15.

The start-up time for this energy storage medium is also fast and is usually less than five minutes [100]. Fig. 16 represents a low temperature adiabatic compressed air energy storage system with thermal energy storage medium, as well as 2 tanks. The hot tank-in the event of charge storage- serves as the medium for the storage of the liquid. The cold storage tank is used for the opposite conditions. The liquid is transferred via heat exchangers for cooling or preheating the air during charging or discharging respectively. These novel thermal energy storage systems also come with advanced control systems.

Considering the thermodynamic principles for a system in quasi – stationary operation, the adiabatic method can best be analysed using Eq. (1).

$$P_{el} = \dot{E}_{air}(T,p) = \dot{m}xe_{air}(T,p) = \dot{m}x\left[T_a\cdot c_p^o\cdot(T/T_a - 1 - In(T/T_a)) + \ T_a\cdot R_L\cdot \ln(p/p_a)\right] \quad (1)$$

Where; P_{el} = electrical power, $\dot{E}_{air}$ = Compressed air, T = temperature, P = Pressure, e_{air} = Specific energy, c_p^o= Specific isobaric heat capacity (1.007 kJ/KgK), Ta = Ambient temperature Pa = Ambient pressure, RL = Specific gas constant (0.287101 kJ/KgK)

Eq. (1) explains how electrical energy can be stored as exergy of

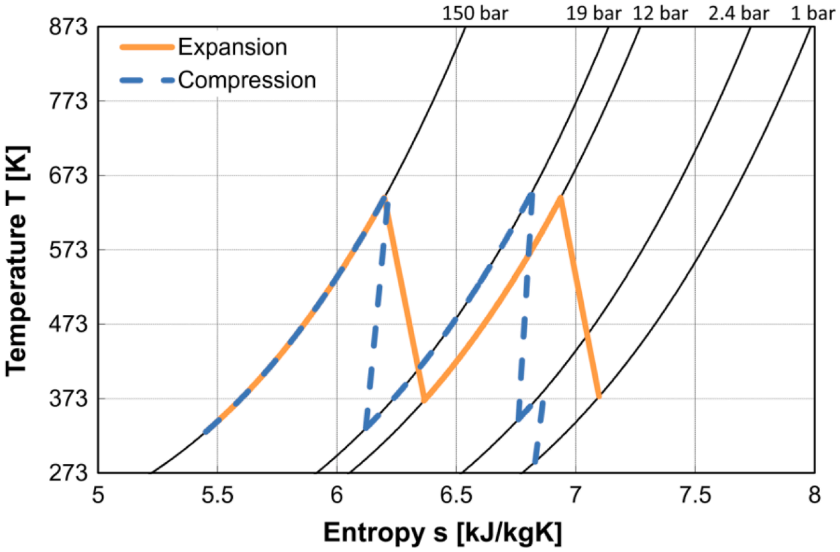

Fig. 14. T, S diagram of medium temperature adiabatic compressed air energy storage [95].

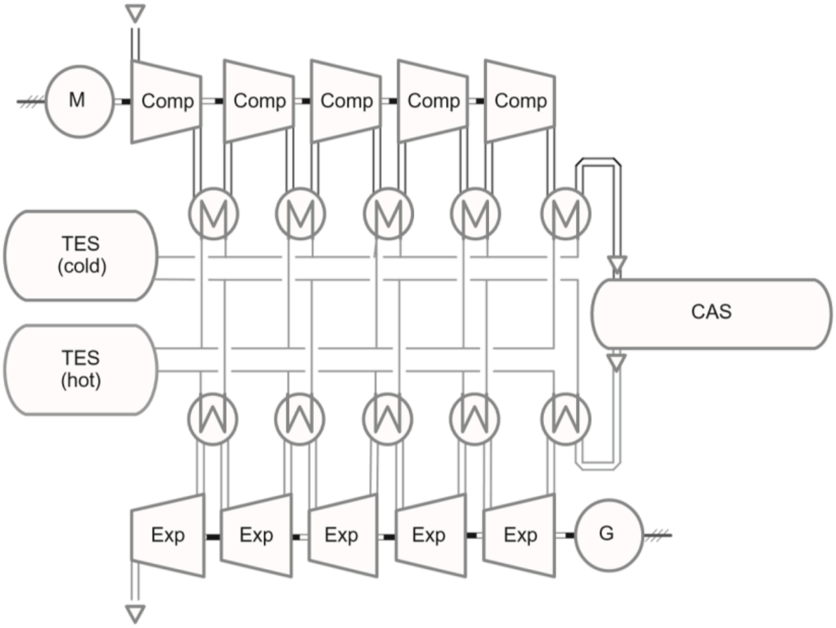

Fig. 15. Medium temperature adiabatic compressed air energy storage [41].

compressed air in an idealized reversed process.

The Adiabatic method achieves a much higher efficiency level of up to 70%. In the adiabatic storage method, the heat, which is produced by compression, is kept and returned into the air, as it is expanded to generate power. When the heat is stored at lower temperatures, the contribution of pressure tends to increase favourably. The German energy company RWE power is currently working on this type of development. The project is called Adiabatic Compressed-Air Energy Storage For Electricity Supply (ADELE).

2.1.1.4. Application example: RWE – ADELE project. RWE is Germany's biggest power producer regarding the extraction of energy from raw materials. They rely mainly on nuclear power, gas and hydropower to produce electricity [101]. They are leaders in 30% of the electricity produced in Germany and a third of that produced in Europe. By 2020 it is estimated that Germany's power generation is to rise, and a new build of wind energy and solar will be the biggest of its kind. Wind itself will produce 50,000 MW of power. Solar is weather dependant, and also extremely intermittent. The plant currently stores 1000 MWh of electrical energy [29].

RWE is designing the project to develop the adiabatic type of compressed air energy storage system (CAES) [102]. The operator of the power plant is currently drawing up requirements such as deployment strategy, availability, operating and safety issues, including vetting for feasible locations. The system design is the core task of the project, operating under the lead management of GE Global Research in Garching. Engineers are working to clarify the overriding mechanical engineering and thermodynamic issues, while also working out the best configurators for the compressor, turbine, heat-storage device, cavern and other components.

General Electric (GE) which is developing the compressor faces complex challenges with this type of storage system, as one of the core components is driven by an electric motor. The compressors suck the ambient air, which is compressed up to 100 bars, and then fed into the

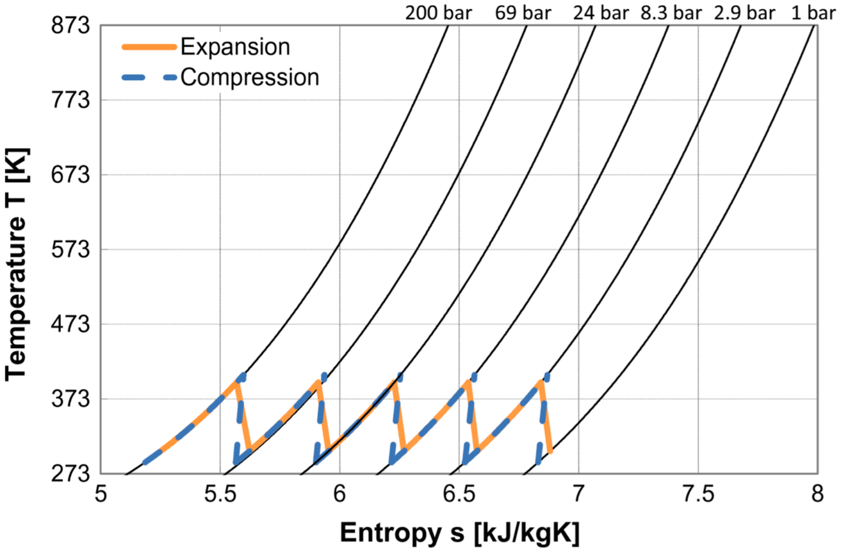

Fig. 16. T, S diagram of lower temperature adiabatic compressed air energy storage [95].

heat-storage device as hot compressed air [103]. GE is facing the challenge to find an alternative, innovative solution for the entire compressor tank, which would become much more aerodynamic, while also meeting demand and ensuring high efficiencies [[104],[105]].

2.1.2. *Diabatic*

Diabatic storage systems utilize most of the heat using compression with intercoolers in an energy storage system underground. During the operation, excess electricity is used to compress the air into a salt cavern located underground, typically at depths of 500–800 m and under pressures of up to 100 bars. When the stored energy is required, air is released and heated by combustion of fuel or gases, and is expanded to power a turbine, generating electricity. The diabatic system is known mainly to be a hybrid system composed of natural gas combustors that utilize the highly compressed air to enhance the combustion process [105]. The world presently has two large-scale CAES plants, namely the 321 MW plant by E.ON Kraftweke, Huntorf (Germany) and the 110 MW plant for PowerSouth Energy Cooperative. Some literature describes diabatic compressed air energy storage systems as “gas turbine cycles”. They are therefore, considered as thermal power plant that functions based on the Brayton cycle. The thermal efficiency of the plant predicts the overall performance of the system. For heat engines, increase in the difference in temperature between the sources of heat results in an increase in the cycle efficiency. In diabatic compressed air energy storage systems, off-peak electricity is transformed into energy potential for compressed air, and kept in a cavern, but given out when demand is high. Fig. 17 shows the schematic of a diabatic compressed air energy storage system.

2.1.3. *Isothermal*

In isothermal compression the air is stored near ambient temperatures until it is required to avoid the challenges associated with temperature control. Once the power is required, the isothermal system uses electrical energy in order to reach the required temperature, meaning that no combustion is required to make this approach much greener [30]. This type of energy storage is often compared to the Ericsson cycle. The round tip efficiency of Isothermal compressed air energy storage system is high compared to that of other compressed air energy storage systems. The temperature produced during compression as well as expansion for isothermal compressed air energy storage is deduced from heat transfer, with the aid of moisture in air. The two-phase movement of air as well as droplets can also lead to this phenomenon occurring.

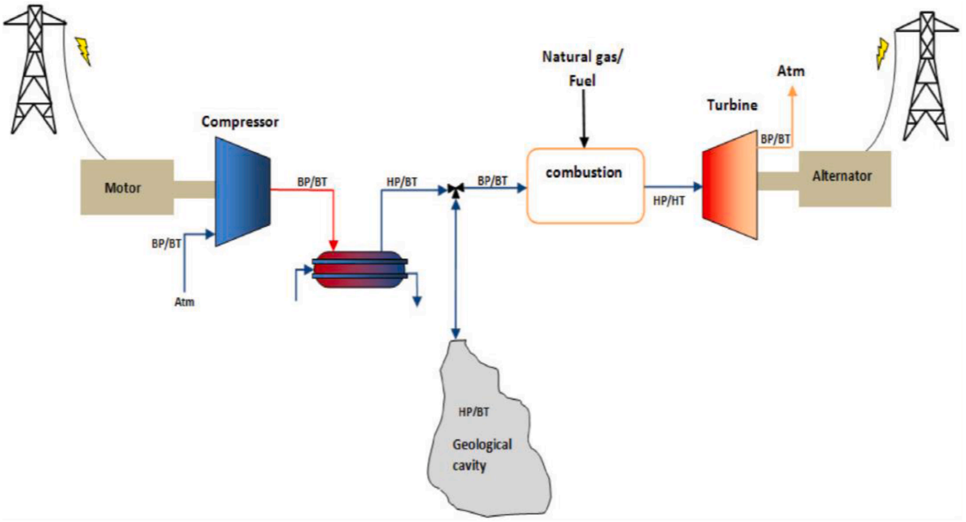

Fig. 17. Diagram of diabatic compressed air energy storage system [106].

The thermodynamic work during expansion, as well as compression, is lower due to the isothermal process. An investigation conducted concluded that the quasi-isothermal compression along with the process of expansion is usually ideal compared to adiabatic compression, particularly for applications at higher-pressure ratios [85]. Today, due to technological advancements, reciprocating machines are being suggested to enhance the reversibility of gas compressions and expansions [107]. The gas kept in a chamber is compressed or expanded using a column of liquid with the aid of a piston. Fig. 18 shows an isothermal compressed air energy storage system.

The three main approaches to designing a CAES system are shown in Fig. 19, and can be summarized as:

1 D-CAES (diabatic) systems: a diabatic process is defined as: “A thermodynamic change of state of a system in which the system exchanges energy with its surroundings by virtue of a temperature difference between them”. This assumes that there are no heat collection systems (heat exchangers) associated with the facility and thus during compression, heat is transferred directly to the surroundings, thereby causing waste. Such systems will require an external heat source during expansion (decompression) to prevent condensation, or worse, freezing in the air turbine stage. In this case and to provide this external heat, fossil fuel must be burnt with the consequent flue gas emissions and loss of the heat generated during compression.

2 A-CAES (adiabatic) systems: These are the most widely used design approach. The heat generated by compression is transferred and stored in a thermal energy storage (TES) system, which is later utilized during the expansion process. There are also Advanced A-CAES (AA-CAES) technologies that have been available quite recently (since 2015) that uses state-of-the-art ceramic heat exchangers to provide the required high heat transfer efficiencies.

3 I-CAES (isothermal): These systems are still under development and require specialized machines to handle the heat exchange. The temperature rise of the compressed gas is assumed to rise in quasi-equilibrium steps where heat is transferred almost instantaneously, thereby preventing the compression-process temperature rise and expansion-process temperature drop. Quasi-isothermal compression is yet to be applied in industrial CAES installations, and methods to expedite heat transfer include augmenting the heat exchanger surface area by spraying a liquid heat transfer material into the chamber of the heat exchanger. This methodology has its serious drawbacks and did not find a wide-scale industrial implementation.

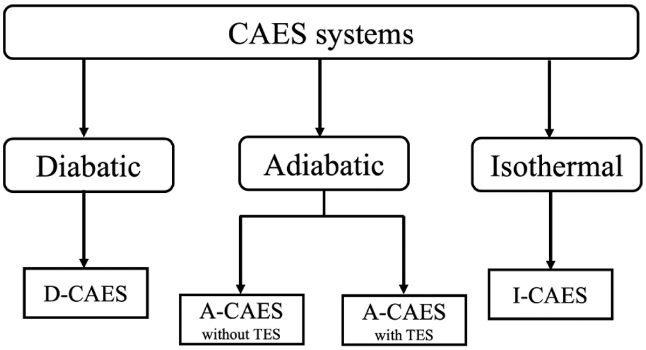

Fig. 19. Classification of CAES systems according to how the compression generated heat is handled.

It is interesting to note that the difference between adiabatic and isothermal assumptions is only apparent as boundary conditions of the partial differential equations that need to be solved in order to predict the behaviour of the fluid. It is intuitive that the lack of a temperature difference between two points (isothermal) can cause no heat transfer (adiabatic), but as boundary conditions they appear as: $\Delta T = 0$and $\dot{Q} = 0$, respectively.

3. CAES system components

In general terms, Compressed air energy storage (CAES) is very similar to pumped hydro in terms of the large-scale applications, as well as the capacity of both in terms of output and storage. However, instead of pumping water from the lower reservoir to the higher reservoir as in the case with pumped hydro, CAES compresses ambient air in large underground storage caverns in times of excess power. This compressed air is held at this storage pressure and then, in times of energy deficiency, this pressurised air is heated, and expands in an expansion turbine which drives a generator that helps to meet power supply demand. An example of a CAES system attached to a wind turbine is also shown below in Fig. 20. The two most important factors regarding a CAES system are the Compressors and Expanders and Air Reservoirs.

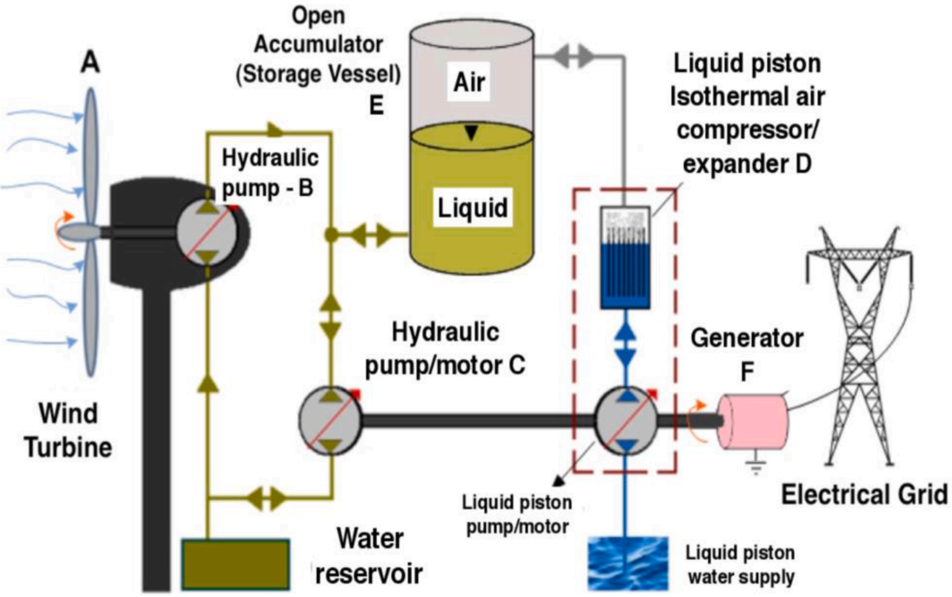

Fig. 18. Isothermal compressed air energy storage system [108].

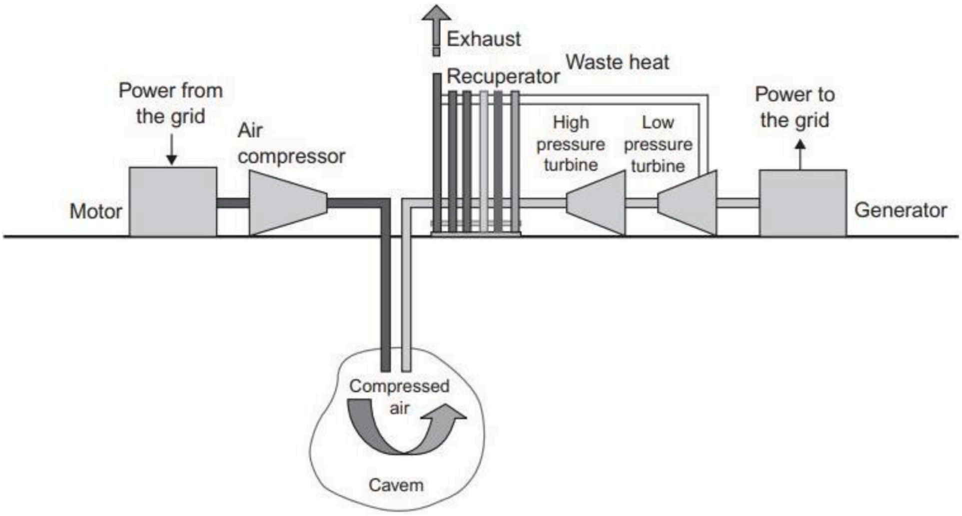

Fig. 20. Schematic diagram of a CAES system integrated to a renewable source [109].

3.1. *Compressors and expanders*

These components, as shown in Fig. 21 are selected or designed based on the size of the CAES system and their requirements. In some large-scale systems, the pressure can be up to around 8Mpa. These systems have multistage compressors and are usually used in combination with axial flow compressors and centrifugal compressors. There are also different levels of expansion. Steam turbines are typically used for the first level of expansion from 4.6 MPa - 1.1 MPa. Gas turbines are then used to convert from 1.1 MPa to atmospheric pressure. The different types of expanders are captured in Table 3.

3.2. *Operational characteristics of the expanders*

The operation of expanders is the reverse of that of compressors. Compressors are typically needed in various applications from refrigerators to jet engines. The types of expanders available today are also dependant on the compressors being manufactured. The reverse operation of both components to each other determines their design when integrated on a compressed air energy storage system. The screw and scroll are two examples of expanders, classified under reciprocating and rotary types. There are other types of expanders such as the axial and radial type, classified under dynamic machines. Positive displacement expanders operate in an intermittent state and are therefore considered as being naturally cyclic. There is also constant operation without any obstruction for the flow of dynamic expanders. Fig. 22 shows the operational range for various types of compressors.

Analysis of compressed air energy storage systems is usually conducted by taking both compression and expansion stages into consideration using ideal gas laws. Expanders' mechanical work is first transformed. The enthalpy transformation of air in the various types of compressed air energy storage systems varies depending on the expansion trajectories. The expansion stage for diabatic and adiabatic compressed air energy storage systems are described as isentropic processes that occur in the absence of heat transfer within the environment. In the event that heat transfer occurs with the environment, the process is considered polytropic expansion. Expansions in adiabatic and diabatic compressed air energy storage systems tend to vary because these two storage technologies undergo various heating as well as cooling processes. An equation to represent the expansion processes can be denoted by Eq. (2) from the ideal gas low theory.

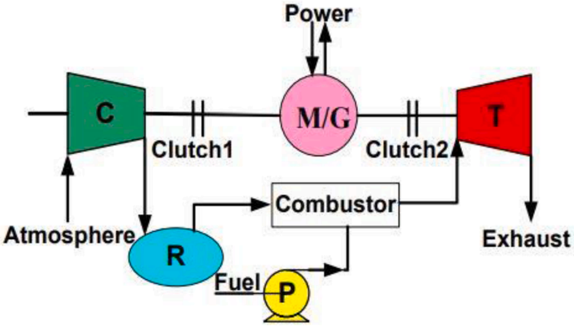

Fig. 21. Compressed air storage system (C—Compressor, G-T—Gas turbine, M/G—Motor/ Generator, P—Pump, R—Reservoir) [31].

$$pv^n = const \tag{2}$$

An index representing the various stages of operation is represent by n. When $n = 0$ the process is represented as isobaric. For $n = 1$, the process is isothermal. When $n = k$ the process is described as isentropic. Polytropic process is when $1 < n < k$ or $n > k$. p *and* $v$are the pressure and volume of the air respectively. The expansion of air in the expanders contributes to variations in air enthalpy. Eq. (3) is used to represent reversible specific isentropic expansion work of air.

$$\Delta h^s = \int_{in}^{out,s} vdp = k/k-1\ RT_1\left[\left(p_{out,s}/p_{in}\right)^{(k-1/k)} - 1\right] \tag{3}$$

The initial and final steps for the expansion process are denoted as in and out. Isentropic step is represented by s whiles T and R denote temperature and gas constant respectively, with h being enthalpy. The specific heat ratio is represented by k.

The ideal gas law for air is denoted by Eq. (4)

$$pv = nRT \tag{4}$$

The isentropic expansion temperature at the outlet can also be determined using Eq. (5)

$$T_{out,s} = T_{in}\left(p_{out,s}/p_{in}\right)^{(k-1/k)} \tag{5}$$

The reduction in the gas enthalpy during expansion based on the polytropic efficiency is developed from Eq. (6), where $n^p_{exp}$is the polytropic efficiency and p denotes the polytropic steps. For a polytropic process the temperature is k is replaced with n.

$$\Delta h^p = n^p_{exp} \int_{in}^{out,s} vdp = n^p_{exp} n/n-1\ RT_1\left[\left(p_{out,s}/p_{in}\right)^{(n-1/n)} - 1\right] \tag{6}$$

When $n = 1$, from Eqs. (2) and 4, changes in air enthalpy between the

Table 3
Types of expanders.

Types of expander	Speed	Cost	Merits	Demerits	Reference
Radial – inflow	8000 - 80,000	High	- Light weight - Mature manufacturability -High efficiency	- High cost - Low efficiency in off design conditions	[155]
Scroll	<6000	Low	- High efficiency - Simple manufacture - Light weight - Low rotate speed - Tolerable two phase	- Low capacity - Lubrication and modification requirement	[154]
Screw	<6000	Medium	- Tolerable two phase - Low rotate speed and high efficiency in off design conditions	- Lubrication needed. - Difficult to manufacture and seal	[146]
Reciprocating piston	–	Medium	- High pressure radio - Mature manufacturability - Adaptable in varying conditions	- More movable parts - Heavy weights	[123]
Rotary	<6000	Low	- Tolerable two phase - Torque stable - Simple structure - Low cost and noise	- Lubrication requirement and low capacity	[142]

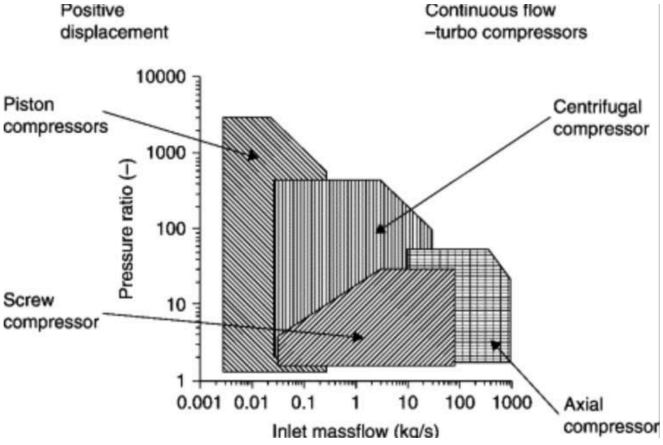

Fig. 22. Operation characteristics of varying compressors [110].

inlet all the way to the outlet for an expander isothermally can be denoted by Eq. (7).

$$\Delta h^t = \int_{in}^{out,\ t} vdp = R\ T_1 In\left(p_{out,t}/p_{in}\right) \tag{7}$$

It must be noted that despite the fact that air is considered as an ideal gas in most research investigations, the application of real gas model will enhance the prediction of the expansion work, as well as the change in enthalpy of the air via the expander in compressed air energy storage system processes. The effect of real gas characteristics on compressed air energy storage systems has also been investigated in literature [41]. The application of isobaric capacity was utilised in this investigation. The researchers showed that performance of adiabatic compressed air energy storage systems was dependant on the application of real gas properties. [41]. The work concluded that the deviation in terms of the isobaric capacities for both the ideal and real gas models increased as pressure increased, and also decreased with respect to temperature [111]. The work further explained that using real gas properties gave completely different results compared to the ideal gas properties when the temperature of the air was reduced at higher pressure. The presence of water in compressed air energy storage systems improves the efficiency of the system, hence the reason for water vapour being injected into the system [[112],[113]]. This water vapour undergoes condensation during cooling in the heat exchangers or the thermal energy system [[114],[115]]. Using real gas models for humid air can be used to easily predict the performance of these storage systems. The modelling for real gas effect has also been investigated by many academics [116–118]. Due to technological advancement, there are software designed to include real gas models [[119],[120]]. In modelling, the geometric design for expanders is very important, compared to that of analysis being conducted thermodynamically. The operational characteristics of expanders are dependent on the type of model used. The models are categorised into geometry based, empirical, and semi empirical. The use of experimental data is directly linked to the empirical model. Expander characteristics are denoted in the form of an algebraic expression using this model. There is no need for iterative numerical methods when using these models. Due to the number of computations being very low, the empirical models are ideal for dynamic modelling. The main limitation for this model is the fact that the model lacks physical meanings and ideals for certain specific designs. The entire physical process for an expander via the inlet to outlet is derived using the semi empirical model. The semi empirical model also uses experimental data. Due to the level of accuracy obtained, the time taken for simulations to be completed using this model is slow compared to that of the empirical model. Deterministic models also referred to as geometry-based models, are developed based on geometric characteristics of the expanders. Using conservation law of mass, momentum and energy, the model can determine the changes in the flow via the expansion process. Using computational fluid dynamics (CFD), the performance of the expanders can easily be simulated. Using computational fluid dynamics is quite difficult compared to the empirical and semi empirical methods. The computational fluid dynamics also involves longer time to generate a solution compared to other models discussed. At the system level, the CFD are ideal for optimisation of an expander and not usually good for dynamic simulation of the expander for varying operations. One method of reducing the computational time for the geometry-based model is to design the geometry as one dimensional instead of three.

3.2.1. *Reciprocating machines*

Reciprocating machines have been utilised as either compressors or expanders in many research activities. Some of the earliest types of compressors are the reciprocating compressors. Their applications span from the industry to various homes across the globe. They are designed as intermittent flow machines. The machine is made up of a piston positioned in a cylinder. The continuous movement of the piston supports the increase in pressure from the gas from one level to the other, as depicted in Fig. 23.

The reciprocating machines are made up of a frame, crankshaft, piston rod, cylinder, and valves. The gas moves into the intake valve after being compressed, and then flows into the cylinder. The piston with the aid of crankshaft supports the expansion of the gas. After the gas finishes expanding, it flows through the discharge valve. Mechanical

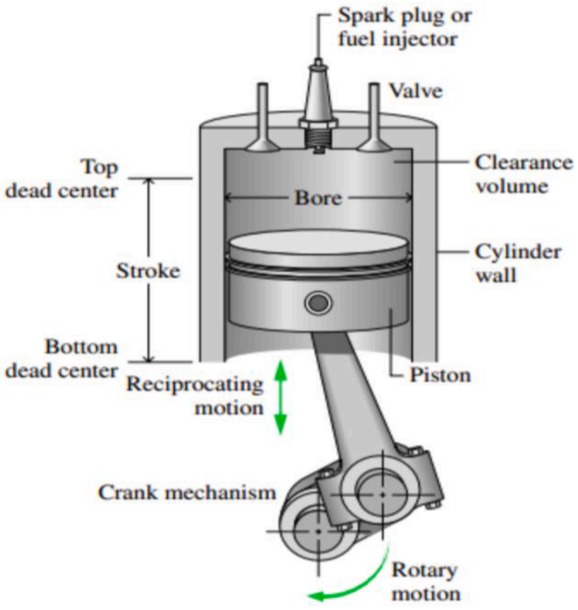

Fig. 23. Components of reciprocating machine [121].

energy is produced due to the conversion of the potential energy in the gas. It is difficult to control the time of opening and closing of the valves. The intake valve for instance allows the passage of air only at a specific pressure. Lower flow rate but higher-pressure ratios are some characteristics of reciprocating expanders. The rotary expanders normally have a higher rotational speed compared to reciprocating expanders. Using speed reduction gears as well as the attachment of the expanders directly to the generator can significantly increase the rotational speed for reciprocating expanders. The isentropic efficiency for reciprocating expanders is higher than 76%. Some researchers also reported their efficiencies being lower than 50% [[122],[123]]. Micro, as well as small-scale compressed air energy storage systems can be made from reciprocating expanders. To enhance the energy as well as power density for these micro-scale systems, using reciprocating machines is ideal due to the fact that these micro systems have lower a flow rate and storage capacity. The internal volume ratio from 6 to 14 makes reciprocating expanders ideal for these micro scale systems also [40]. The manufacturing of reciprocating expanders can be traced to the early 1970s [124]. Investigations on reciprocating expanders using waste heat recovery as well as pressure ratio from 20 to 40. The rotational speeds of 500–6000 rpm has also been investigated [125]. A group of researchers explored the performance of reciprocating machines in an ORC system under medium temperature conditions. The temperature was managed by ensuring the condenser temperature, as well as the cut of angle was controlled. The investigation concluded that the isentropic efficiency of the expander at large pressure ratios beyond 20 was nearly 90% [126]. Using a swatch plate expander, another group of researchers experimentally analysed the performance of this piston expander. The pressure ratio for this investigation was carried out ranging from 18 to 30 bars, and the speed was kept in a range from 1000 to 4000 rpm [127]. Cryonic energy was also transformed to mechanical energy using a reciprocating expander in a Stirling cycle [128]. Reciprocating expanders are designed to be flexible and are hence operational even at varying conditions. They are also ideal in terms of being connected directly to the crankshaft [129]. Reciprocating machines are also ideal for applications with lower pressure ratios [[130],[131]]. Research has also revealed that reciprocating expanders are tolerant to moisture as well as 2 phase flows [[132],[133]]. This shows that reciprocating machines can be used effectively in isothermal compressed air energy storage systems.

The main limitation for these types of expanders has to do with cost due to moving parts. Most costs are attributed to the maintenance of the expanders due to moving parts. They are also bulky and are usually not the most preferred type of expanders. The flow rate, as well as the power output is reduced for the reciprocating expanders [134]. Newly developed piston expanders enhance the transfer of heat via an isothermal process [[135],[136]]. Designing the valves, pistons and cylinders are key components that must be developed before modelling. Using 7 input parameters, an investigation on a steady state semi empirical model made up of 5 processes was investigated in literature [137]. The same concept was adopted in other studies in literature [[138],[139]]. The entire expander model is made up of many stages as depicted in Fig. 24a below. The fluid in the expander goes through many stages such as: drop in pressure; cool down, expansion, and loss in pressure at the exit, as shown in Fig. 24a. There are instances where there is internal leakage as well. Fig. 24b shows the entire process in a reciprocating expander.

3.2.2. Rotary expander: screw and scroll expander

These types of expanders are usually made up of rotors designed in a helical shape and kept in an enclosure. Fig. 25 shows a single screw expander, while Fig. 26 shows a twin screw expander. Intermeshing of the motor causes expansion to occur. The rotor for screw expanders operates using gas that is compressed. The rotor on the other side operates either with or without an oil injection. The rotation of the rotors cause gas to enter the expander because the intermesh space tends to increase as well. Once these spaces are filled, there is expansion of the gas due to the rotors rotating at a constant speed. The gas is then made to flow to a discharge port. There is a reduction in pressure at this stage but an increase in the volume of the gas. The continuous rotor rotation exposes the discharge port, allowing the exhaust gas to exit the expander. Screw expanders are normally made up of a rotor and 2 gate rotors. These rotors are responsible for all of gas intake, expansion, and the exiting of the gas from the expanders. The rotor design and porting have an enormous impact on the efficiency of the screw expander. The flow rate of the gas is influenced by the diameter and length of the rotor. Pressure ratio tends to be higher when the rotor is longer, and when the diameter of the rotor is large; the screw capacity tends to be higher as well. The screw expanders have lower pressure ratios compared to the piston expanders. Output power obtainable from screw expanders varies between 1.5 kW to 1MW [142–146]. There is a need for a speed reduction gearbox for screw expanders because they tend to have high rotational speed. This is important so that the speed of the screw expanders is similar to that of the generator. These types of expanders are also ideal for isothermal compressed air energy storage systems because they support two-phase flow. The leakage losses for screw expanders are high, hence not ideal for capacity lower than 10 kW [147]. There are two different types of leaks in screw expanders. There are leakages between the discharge port and the expansion chambers. The leakages can be prevented via design and optimization of the rotor. This strategy is also capable of reducing losses due to friction. Scroll expanders are usually ideal when the application needed has small capacity for power. Scroll expanders are designed to have fixed scroll as well as 2 involutes, as captured in Fig. 27.

The orbiting scroll operates using compressed air in a scroll expander. It is then made to go around the fixed scroll. There is a formation of pockets due to the meshed scrolls formed during rotation. There is movement of air into the intake for the scroll expander. The expansion chamber increases due to the orbiting scroll moving. This causes the compressed gas pressure to reduce. Continues rotation of the orbiting scroll allows for the release of the gas into the exhaust chamber. Scroll expanders are designed to be small when compared to the size of screw expanders. Their pressure ratios are therefore lower compared to those of screw expanders [[149],[150]]. One phenomenon that occurs in scroll expanders is the possibility for an over or under expansion occurring, because the internal volume is more than the volume ratio needed by the pressure ratio. Many research activities have been conducted on rotary expander applications. This is due to the fact that rotary expanders have few moving parts, and their design in terms of

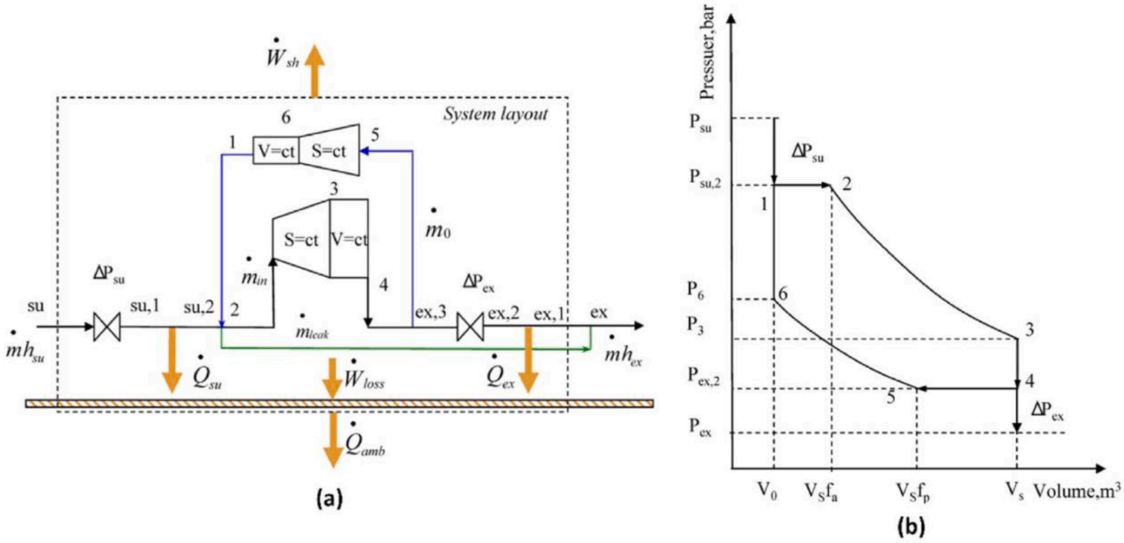

Fig. 24. a) Overall expander model b) P – V diagram for a reciprocating expander [125].

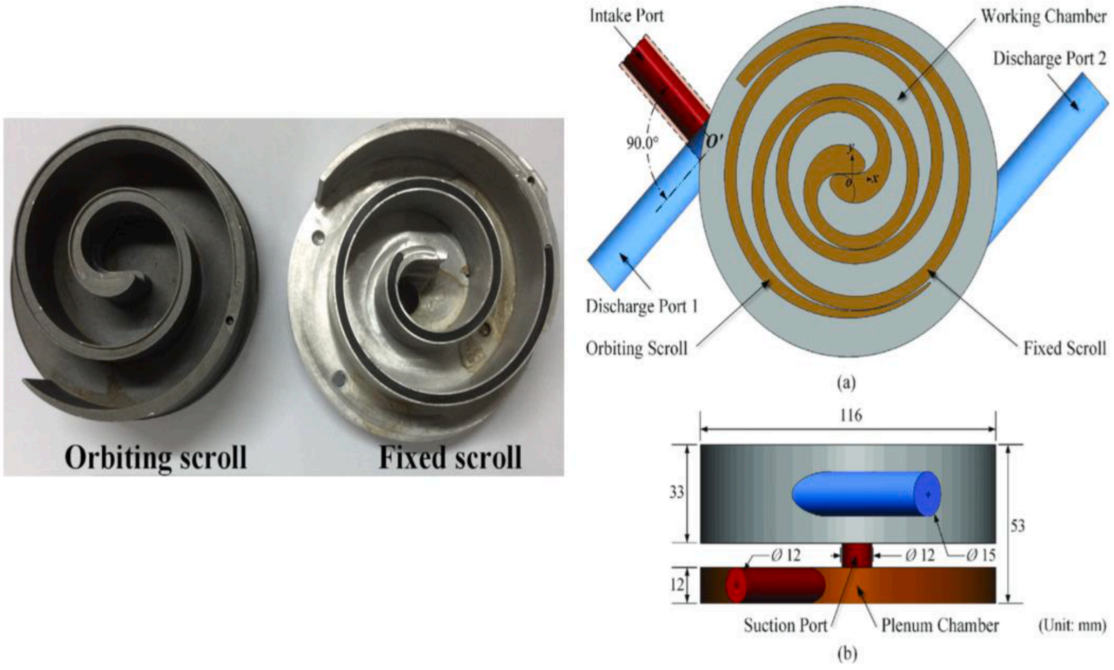

Fig. 25. Single screw expander [140].

structure is simple. They are also cheap compared to the other types of expanders. A research piece that was conducted for a single screw expander with an output of 200 kW concluded that the efficiency for the expander used was 55%. There was variation in pressure at the intake from 4 to 16bars [151]. Another single screw expander was also investigated in literature, with an efficiency being over 50% [152]. A single screw compressor having built in volume ratio of 5 in terms of volume was also investigated in another study. The maximum output power at 3000 rpm was noted as 7.8 kW. The isentropic efficiency for the modelled single screw compressor was 64.7% at pressure ratio of 7.7 [153]. Conditions surrounding the fluid at the inlet with respect to pressure ratio have also been investigated. The researcher attempted to document efficiency for a single screw expander [143]. Investigations on rotor forces produced by expanders were conducted to remove axial forces, hence reducing the bearing forces radially using twin-screw expanders [154].

3.2.3. Radial and axial expanders

These types of expanders are classified under dynamic expanders. They are made up of impellers. There is a transformation to kinetic energy, due to the movement of the impeller and the thermodynamic conversion of energy in the fluid. They are also designed to have a reverse gas flow and have an opposite rotation in comparison to a centrifugal compressor. The passage of the gas into the nozzle occurs after flowing via the turbine. This results in the transformation of potential energy to kinetic energy. The gas after the expansion process flows out of the impeller axially. Radial inflow turbine turns to yield a better output compared to an axial turbine. This is often attributed to the impeller for the radial being large.

The axial and radial turbines are represented in Fig. 28A and B,

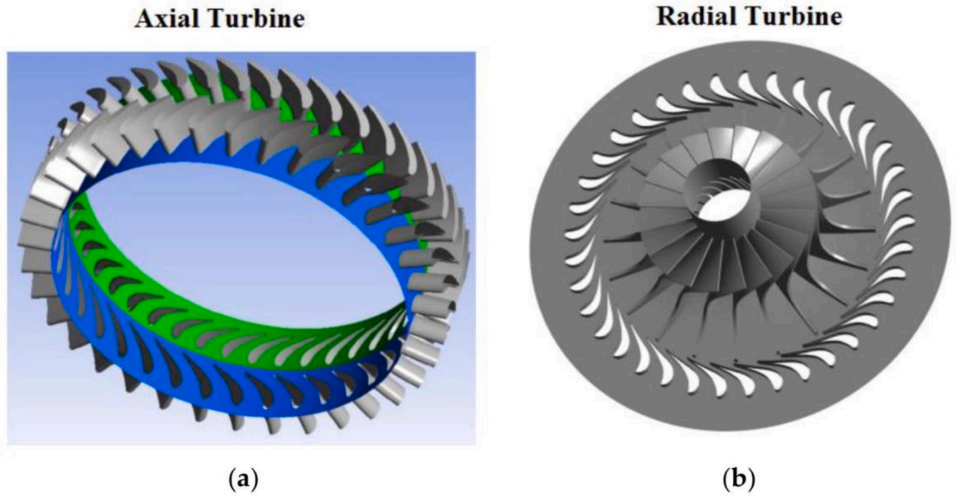

Fig. 26. Twin screw expander [141].

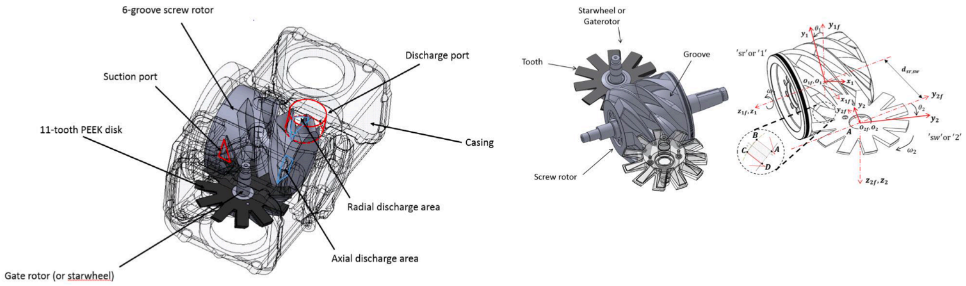

Fig. 27. Scroll expander design [148].

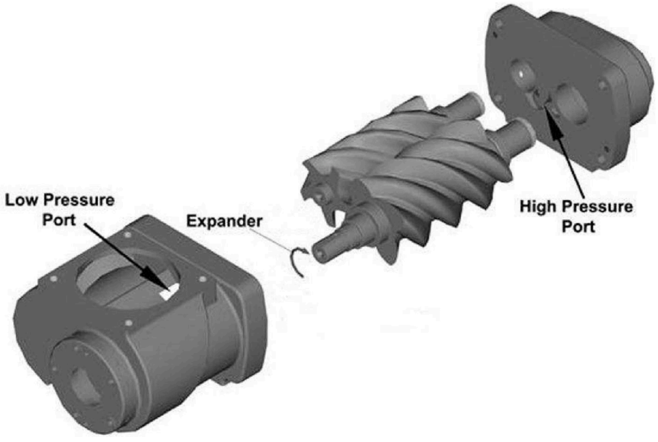

Fig. 28. Diagram for axial and radial turbines [155].

respectively. These expanders support high flows compared to the other types of expanders described above. The pressure ratios are also low. The constant operation of the turbines in the absence of any intermittency results in higher flows. Radial expanders show slight deviation from the phenomenon described earlier. They exhibit a lower flow rate, but high-pressure ratio [156]. Axial expanders are ideal for plants with more than 10MW as their output power. They are categorised under the dynamic machine type. They have high speed, but their pressure ratio is lower compared to that of radial expanders. The movement of the gas occurs in an axial direction inside the expander. They are made up of a cast, rotor and a stator. The inlet angle can be changed via the introduction of another inlet guide vane. They come in power plants for the production of electricity. Rotation of the rotors occurs due to steam devices using thermal energy from the gas being pressurized. Electricity is then produced due to a shaft driving a generator. Producing power can also be done with the aid of a gas turbine, and the working fluid being air. Movement of fresh air via the compressors increases the pressure. The mixture is ignited as a result of spraying fuel into the air. The burning process therefore leads the temperature of the air to be high, along with the pressure. This determines the mechanical work generated in axial turbines.

Radial and axial expanders have been utilized in a number of compressed air energy storage systems, particularly for large-scale applications. Turbo machines are functional at higher rotational speeds. They exhibit lower pressure ratio but higher flow rate. They are normally not ideal for isothermal compressed air energy storage, due to challenges relating to moisture and two-phase flow. There is a high similarity between the turbines for power plants those of adiabatic compressed air energy storages and those of diabatic compressed air energy storages. The inlet temperatures for the turbines have an enormous effect on both the efficiency and design of the turbine. The Gas turbine cycle as well as Rankine cycle is used to determine the performance of these turbines. Reducing pressure drops will significantly enhance the performance of these types of turbines.

3.3. *Criteria for selecting compressed air energy storage system expanders*

The efficiency of all expanders is dependent on the thermodynamic characteristics of the working fluid. It is therefore important that a clearly defined criterion is adopted to support the selection of expanders for compressed air energy storage systems. Compressed air energy storage systems are made up of various parts with varying functionalities. A detailed understanding of compressed air energy storage systems paired with an in-depth comprehension of various expansion stages of air will form the basis for any selection criteria. The overall process of expansion is also crucial, so is fixing the operating pressure conditions as well as temperatures and flow rates. The system scale is a function on the type and capacity of expanders selected. It also helps determine the expected operating conditions of the expanders. Also, the number of expanders coupled to a shaft in series determines the expansion stage number and the Any pressure losses will lead to higher running costs and thus the optimization of the stage number becomes necessary. For diabatic compressed air energy storage, it is possible to generate higher powers due to the integration of fossil fuels especially during the expansion of air. The compressed air stored is therefore not used entirely during electricity production.

Operating air pressures for the McIntosh as well as Huntorf are in excess of 46 bars. These systems come with an air expansion as a turbine train. For lower diabatic compressed air energy storage systems with pressures below 12 bas, an LP air expansion train is utilized. The investigation showed that a temperature of 900 °C was recorded via a cascaded solar heating [157]. Air expansion is very is important in an adiabatic compressed air energy storage system since there is no combustion of fossil fuels in these storage systems. The energy generated from compressed air as well as the heat must be well utilised as well. The air expansion stages, as well as the inter stage heat exchangers are designed to be equal in adiabatic compressed air energy storage. This integrated with heat exchangers as well as sensible storage. Reducing exergy loss during the air expansion as well as pressure loss in the heat exchangers is dependent on the stage number for the air expansion. The most common compressor type is multistage compression with inter stage cooling. The stage number for the entire expansion ratio is largely dependent on the type of expander [158–160]. An adiabatic compressed air was developed with a discharge rating in terms of power being 500 kW. The discharge pressure was also maintained at 2.5 MPa. The heat storage for this system was also made to contain water with a temperature of 110 °C [161]. The pressure ratio designed for this investigation was 2, 2.8 and 3.9. For some adiabatic compressed air energy storage systems, the number of inter stage heating is dependent on how the heat is stored [162]. Fig. 29 summarises information on the various types of expanders for varying compressed air energy storage systems.

3.4. Air reservoirs

Due to the nature of the technology, large volume air reservoirs are essential for effective and efficient operation of the system. Current CAES systems utilise large underground storage systems. These reservoirs are usually made in underground salt, hard rock and porous rock layers. These natural reservoirs have inherent problems, such as problems caused by animals like rats, and problems with salt water. At the end of each discharge, there will be left over air in the system, which affects the overall efficiency. In constant pressure systems, the systems keep high efficiency in both the charging and discharging phases [95]. Table 4 shows the cost in terms of the types of storage, power rating and the duration for the storage. The cost from Table 4 is divided into the cost of power related components, such as: turbine and expander and the cost of storage components such as underground caverns and over ground cylinders. Presently, the two commercially available compressed air energy storage systems use salt caverns as the air storage reservoirs. The Huntorf has a storage capacity of 310,000 m^3; the McIntosh on the other hand has a storage capacity of 560,000m^3.

Isobaric or isochoric storage is the most commonly used compressed air storage system. It maintains the air at a constant volume or pressure. The pressure of the gas is made to vary for the constant volume storage, and this shows the state of charge. Steel pressure vessels are common examples of isochoric storage. Salt cavern is also another example of isochoric storage. Volume is also varied for the constant pressure storage during charging and discharging. The state of charge in this case, is determined by volume. The application of hydraulically compressed reservoirs can also be a form of constant pressure storage. In this method, there is a second reservoir needed at a specific height, as shown in Fig. 30 below.

The main limitation for isochoric compressed air storage has to do with the impact they tend to have systems during compression and expansion. The expanders must be able to succumb to the changing pressures, meaning they do not function based on their designed pressure ratio. This therefore, reduces the efficiency of the system. For diabatic compressed air energy storage systems, with the application of isochoric compressed air storage, the pressure in the cavern must be throttled, even though it often exceeds the pressure in the combustion chamber. The losses due to exergy are being addressed for newly developed adiabatic compressed air energy storages using the introduction of expanders that are flexible between the compressed air storage and the combustion chamber [165]. Isobaric storages are quite complex, which is why they are not often the best choice for the research community.

Isochoric as well as isobaric compressed air storage systems are ideal for both underground or above storage systems. The compressed air storages built above the ground are designed from steel. These types of storage systems can be installed everywhere, and they also tend to produce a higher energy density. The initial capital cost for above- the-ground storage systems are very high. Availability of land is also another major challenge, along with the cost in maintenance, as pressure must

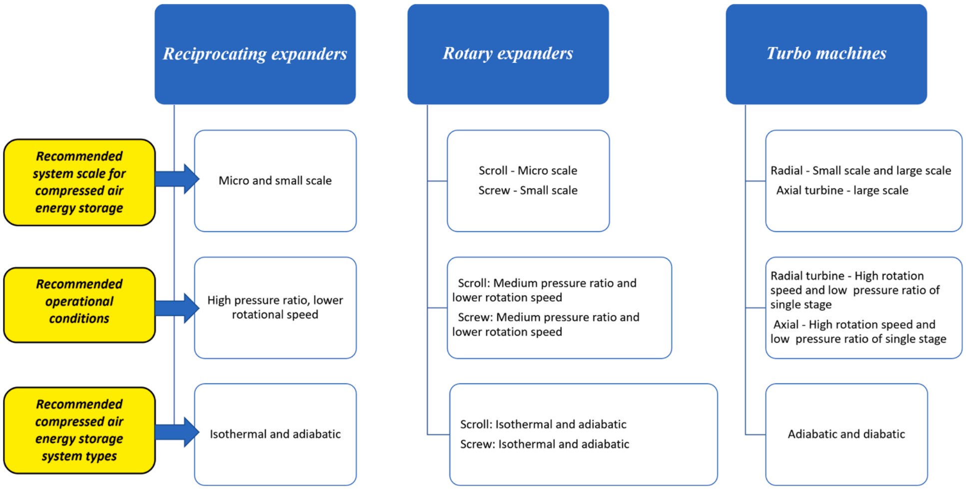

Fig. 29. Comparison for various types of expanders ideal for compressed air energy storage systems from literature.

Table 4
Storage medium and plant configurations.

Reservoir	Capacity ($/kWe)	Power related component($/kW)	Energy storage component($/kWh)	Timing for storage in hours	Total cost ($/kW)	Reference
Salt	200	350	1	10	360	[95]
Porous media	200	350	0.1	10	351	[163]
Hard rock	200	350	30	10	650	[164]
Surface piping	20	350	30	3	440	[165]

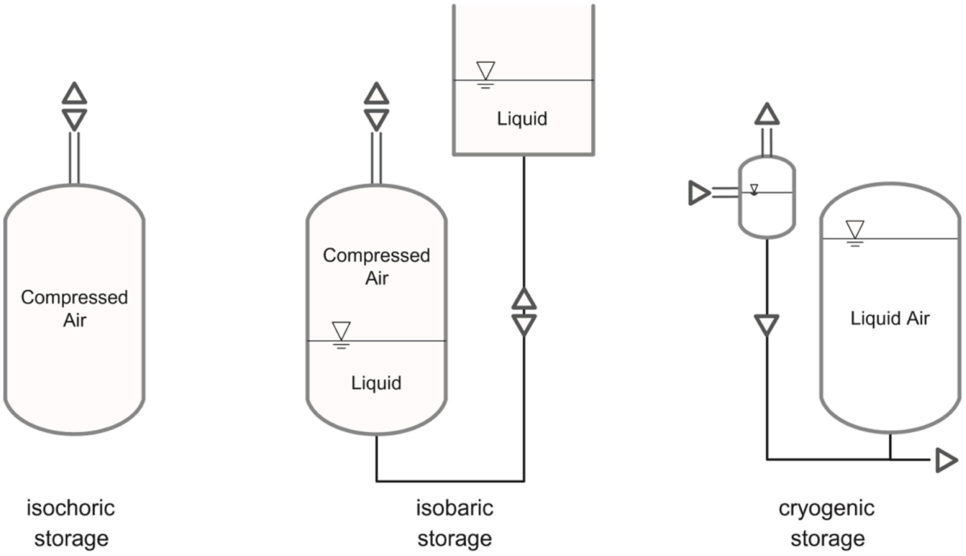

Fig. 30. Varying compressed air storage [95].

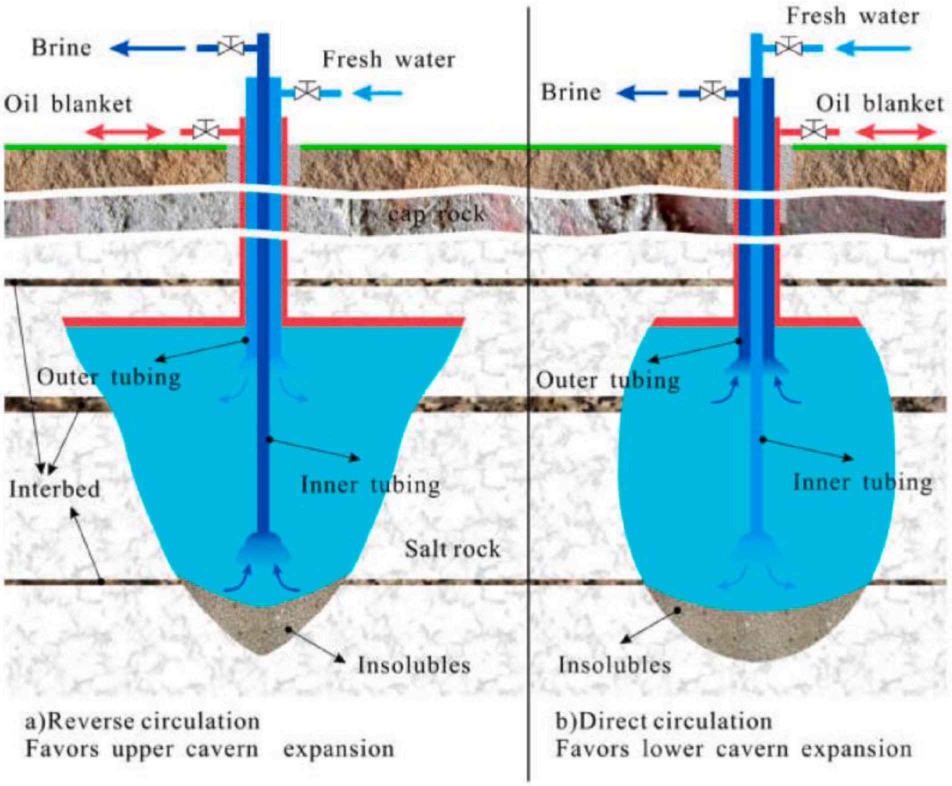

Fig. 31. Salt cavern for compressed air energy storage systems [167].

constantly be checked and regulated.

There are several options for underground compressed air energy storage systems. A cavity underground, capable of sustaining the required pressure as well as being airtight can be utilised for this energy storage application. Mine shafts as well as gas fields are common examples of underground cavities ideal for this energy storage system. This type of system does not require vast land and its initial capital cost is lower compared to above ground compressed air storage systems. The geology of the cavity is very crucial for this type of storage system. The rock stability reduces the pressure difference. The well-known technology for large-scale compressed air storage system is salt caverns. They are currently used for many commercial purposes. Several research activities conducted on natural gas storage yielded positive results to the research community, and the same knowledge is being transferred to designing pressurised salt caverns [164]. In developing salt caverns as shown in Fig. 31, the operating pressure must be maintained at a minimum level in order to sustain any external forces being exerted on them [166].

4. Developments and applications

CAES is still considered to be in the development and demonstration stage of its lifecycle, due to the complexity and problems regarding the efficiency of the systems. There are currently only two operational CAES plants, one in Huntorf, Germany (1978), and another in McIntosh, Alabama (1991). There are a few key differences between these two plants. For example, Huntorf uses two salt caverns at a pressure range of 4.8–6.6 MPa and runs in a cycle of 8 h of compression and 2 h of expansion daily. The plant has a rated power of 290 MW and a cycle efficiency of 42%.

McIntosh operates a single salt cavern reservoir with a pressure range of 4.5–7.4 MPa. The plant utilises a heat recuperation system to repurpose the heat lost at the exhaust of the gas turbine. This system boosts overall cycle efficiency from around 42% up to around 54%. Table 5 summarises the differences between the two compressed air storage systems.

However, recent developments have boosted applicability of CAES systems through a new system known as a compressed air battery (CAB). The key benefit of this CAB system stems from the development of scroll expander technology, which improves expansion efficiency. This system operates by using pre-compressed air, allowing full focus on the expansion process at hand. This way, heat losses and expansion losses are significantly lower. The system can also be used in conjunction with a super capacitor and become a hybrid system. This hybrid approach provides several benefits such as fast response, low start up and maintenance costs compared to other standby batteries, which use electrochemical means as well as having superb power output reliability.

Table 5

Comparison between the two compressed air energy storage systems.

Compressed air facility	Huntorf	McIntosh	Reference
Manufacturer	Browne Boveri	Dressere R and	[97]
Owner	Eon	Power South	[168]
Year of operation	1978	1991	[169]
Plant capacity in MW	290	110	[170]
Charge time, h	8	40	[171]
Maximum charging power, MW	60	50	[172]
Discharge time, h	2	26	[173]
Maximum discharging power	290	110	[173]
Hours of compression/ generation, h	4	1.6	[97]
Power requirement, kWin/kWout	0.82	0.75	[168]
Power plant efficiency	0.42	0.54	[168]
Maximum energy, MWh	480	2000	[173]
Minimum energy, MWh	0	200	[169]
Geology	Salt	Salt	[170]
No. of caverns	2	1	[170]
Air pressure in cavern, bars	46–66	74–45	[97]
Volume in m^3	270,000	532,000	[168]
Depth to caverns in m	500	500	[172]
Geometry	Cylindrical	Cylindrical	[173]
Type of fuel	Gas	Gas/Oil	[169]
Compression power, MW	62	53	[171]
Compression air flow, kg/s	107	93	[171]
Expansion air flow, kg/s	414	156	[170]
Operating pressure, bar	20 – 43	45 – 74	[169]
Amount invested in $	139($480/ kW)	139($480/ kW)	[173]
Compressor efficiency	0.8	0.8	[171]

With regards to future applications, certain areas of potential stand out. CAES has huge potential in terms of its use as an energy management tool. It also has potential with regards to its applicability for peak shaving, as well as boosting power quality. Firstly, the ability to integrate a CAES system into an intermittent power source, such as wind farms, where the power output is not constant can be executed. CAES in this case could be utilised in order to store excess power for use at a time of greater demand. This is possible due to the response time and discharge durations of CAES systems. The application of other compressed air engines can support in converting the compressed air energy into other forms of mechanical energy, which will then be ideal for powering vehicles. CAES can also be used as backup power, which can serve as an alternative source of power for banks, data processing centres and even hospitals.

Certain problems are inherent with CAES. The major issue currently facing the development of the technology is the problems with efficiency in the system and the need for further study into the environmental impact of the technology. These critical issues are impeding the advancement of this technology. Finally, issues regarding the construction costs and types of land required in order to implement such systems are also preventing development. All these primary factors must be addressed in order to make this energy storage system sustainable [33].

5. Health & safety

The main health & safety concern when looking at storing compressed air within underground formations, such as: excavated mine cavities, solution-mined cavities, aquifers and depleted natural gas reservoirs is the fact that different hydrocarbons may be present, resulting in a potential fire hazard [94].

Hydrocarbons are molecular compounds that are made up entirely of hydrogen & carbon atoms and can come in the form of different natural gases such as Methane, Ethane & Propane, for example, which are all highly flammable.

Regarding fire combustion, there are three elements that are required to come together to ignite a fire (oxygen, heat and fuel). The hydrocarbons present within these underground formations are only one of three elements of the “fire triangle”, the fuel. The compressed air, which will then be fed into the underground formation, will provide the second element required for fire combustion, the oxygen. The heat, or ignition source, is the third and final element required to ignite a fire, presuming the hydrocarbons & compressed air are present within the underground formation.

5.1. *Possible ignition sources*

5.1.1. *Heat of compression*

With regards to adiabatic compression, the heat which is generated through compressing air into underground formations can be a potential ignition source. Fig. 32 below illustrates the rise in temperature relating to rise in pressure associated with the compressed air being fed into the cavities underground.

5.1.2. *Lightning*

Lightning, an unavoidable natural occurrence, has also been known

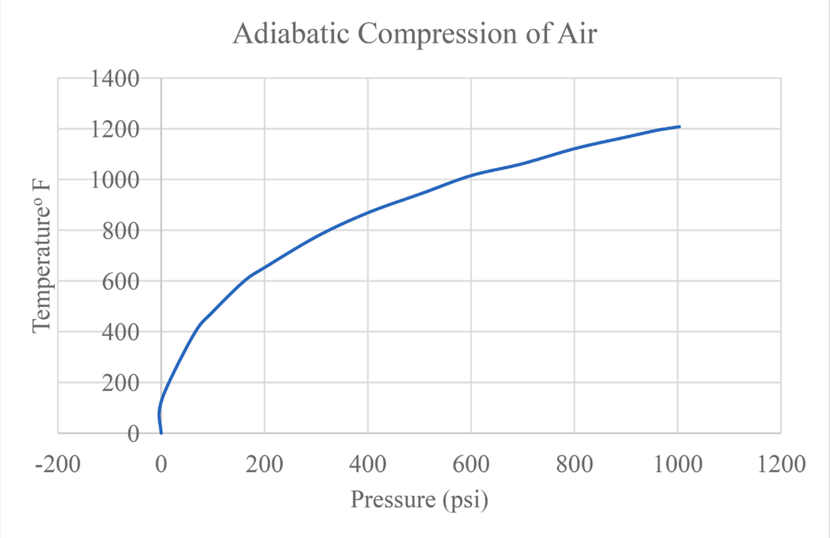

Fig. 32. Temperature-pressure relationship [34].

to contribute to underground fires. With a bolt of lightning reaching temperatures up to ~30,000 °C (Lamb, 2010), this would provide more than enough heat to ignite a fire if it landed in an area near/around the entrance to an underground formation.

5.1.3. *Friction*

Friction is another possible cause of ignition within underground cavities due to potential heat. This heat can be produced alongside the oxygen supply from compressed air & the hydrocarbon molecules that may be present.

When the empty underground formations are being supplied with compressed air or being emptied, the rise and drop in pressures may cause the rocks to rub off one another, resulting in them cracking or breaking. With the rocks rubbing off one another, this can cause them to heat up & expand, creating a potential ignition source within the cavity [172].

The "fire triangle" highlights the three key elements required for fire ignition. However, if all three elements are present it does not necessarily mean that a fire will ignite. Regarding an ignition, the combination of both the fuel (hydrocarbons) & the oxygen (compressed air), must be within the lower & upper explosion limits for one to occur; too much or too little of either will result in no ignition.

5.2. *Safety procedures/practices*

Within any industry when hazards are identified, different safety procedures & practices are developed to either completely remove or mitigate them for the safety of everyone involved. Upon filling the underground formation with compressed air, it is important that the area is purged with the aim of removing all the natural gases that may be present within the area, before the compressed air is fed in. In doing so, this will help significantly reduce or remove any of the hydrocarbons that are present, thereby removing one of the elements required for a fire combustion. Along with purging, an electronic gauge/reader should be present within the underground area, which can determine the amount of natural gas before and after the purge has taken place. Assuming the natural gas levels are now within a safe working limit, a working permit should then be allocated to show that work can begin, and the compressed air can be fed into the underground area.

In the event that a fire does ignite underground, it is vital to have safety measures in place to ensure that the heat/ gases being produced do not surface to the equipment above ground level. To help prevent this from happening, automatic safety valves should be in place that would effectively contain the fire/gases looking to escape and protect the equipment on the ground i.e. the turbine.

It is important to ensure that the balance of both the hydrocarbons (methane in this case), and the level of oxygen present (compressed air) are kept out with both the lower & higher explosive limits to reduce the chances of any fire(s) igniting. This can be achieved through the use of different gauges i.e. knowing how much natural gas is present within the underground formation and controlling how much compressed air will be fed into the formation. In doing so, it can be ensured that the level of both the natural gases & oxygen present are not within the explosive limits.

5.3. *Advantages & disadvantages of CAES*

One of the main advantages of Compressed Air Energy Storage systems is that they can be integrated with renewable sources of energy, such as wind or solar power. In doing so, the renewable energy that is created through the use of wind turbines or solar panels can then be used to compress the air into the underground formations thereby reducing, if not entirely removing the need for fossil fuels at this point.

Another advantage with the use of these systems is that they can be stored underground, increasing the land available above ground that can then be used for other purposes i.e. wind turbines/ solar panels. This, in turn, will then be able to power the motor & compression system to compress the air into the underground cavities.

With a rough estimate of 80% of U.S territory being geologically suitable for CAES, it has the potential to be a leading system within the storing of compressed air energy [103].

One of the main disadvantages associated with this type of storage system is the need for the heating process to cause expansion. With the integration of a renewable energy source such as a wind turbine to help power the heating process, it helps reduce the amount of energy required. However, if fossil fuels are required to add further heat then this can be problematic. With the rise in price for fossil fuels, if too much are required to provide extra heat, the system can become inefficient in relation to the overall costs of producing the energy [104]. Table 6 summarises the primary advantages and disadvantages of CAES systems.

6. Conclusion

Overall, the Compressed Air Storage Systems (CAES) provides an effective way of producing energy for the electrical grid. Utilising other renewable sources of energy like wind and/or solar to provide energy to

Table 6
Advantages and disadvantages of CAES systems in a power generation system.

Advantages	Disadvantages	Reference
Increase usage of the generating facility during off peak hours	The underground geology storage is a major issue due to the presence of hydrocarbons.	[164]
Provides ramping, intermediate and peaking power during the day	Site selection is also another major challenge as there is the need for a site where there are mines, caverns and specific geological formations	[165]
Can store energy generated at night especially for wind energy systems and can be delivered during the higher priced daytime	There are certain losses that are not avoidable hence less energy eventually gets to the grid	[166]
Provides better frequency control compared to load based power plant	The need for additional; heating during the expansion is also another major disadvantage.	[167]
Can be operated 24 h a day in synchronous condenser mode.		
Provide off peak to on peak arbitrage		
Absorbs excess generating capacity with its compressor when demand is low.		
Provides significantly high energy storage at low costs.		
They (Huntorf and McIntosh) also have black start capabilities		
Compressed air storage systems tend to have quick start up times.		
They have ramp rate of 30% maximum load per minute.		
The nominal heat rate of CAES at maximum load is three (3) times lower than combustion plant with the same expander.		

operate the CAES systems seem to be the only cost effective and efficient ways to run them. With the cost of fossil fuels continually rising, along with the need for them to provide extra energy within the heating process, further development is required to advance the renewable energy technology to make it efficient enough to provide all the energy required to run a CAES systems. In doing so, it will eliminate the need for any fossil fuels to be required when running the system, reducing operating costs as well as reducing CO_2 emissions being released into the atmosphere. The commonly used compressed air energy storage systems (diabatic, adiabatic, isothermal) for small to large-scale storage purposes were assessed in this review. It was noted that a diabatic compressed air energy storage system is cheap and ideal for large-scale systems. This storage system is also considered as an advanced technology compared to the other types of compressed air energy storage systems. Adiabatic as well as isothermal compressed air energy storage systems are still undergoing various research activities, in order to accelerate their commercialization. The cost of compressed air energy storage systems is the main factor impeding their commercialization and possible competition with other energy storage systems. For small scale compressed air energy storage systems volumetric expanders can be utilized due to their lower cost compared to other types of expanders. The lower operational speed of volumetric expanders, along with their ease of manufacturing also reinforces their possible application for small and micro scale compressed air energy storage systems. In terms of isothermal compressed air energy storage systems, volumetric expanders can be used as well because they are good at absorbing moisture. Volumetric expanders support 2 phase flows during the expansion stage, hence making them ideal for isothermal compressed air energy storage systems. Diabatic and adiabatic compressed air energy storage systems operated on large scale will yield the best performance using turbo machines. The main challenge with integration of this type of expander on isothermal compressed air energy storage systems has to do with the blade being corroded. Various designs from literature used in modelling expanders were also covered in this review. Ideal methods for the selection of compressed air energy storage expanders were also discussed.

There is still the need for further investigations into reducing pressure drop for diabatic and adiabatic compressed air energy storages. Improving the power generated when the system is being operated under elevated temperature and pressure is also another key area of research. The cost of small-scale compressed air energy storage systems with volumetric expanders can be reduced, provided the capacity for these types of expanders are increased. This can only be achieved with further research activities. Thorough investigation using radial expanders must also be carried out to enhance their efficiency, as well as optimising the existing designs. Developing reliable control systems is another key research direction in this field. Other issues relating to compressed air energy storage systems in general has to do with identifying suitable locations for storage systems due to geographical restrictions. Further investigations into possible alternative sites for compressed air energy storage systems must also be investigated. This must be done taking into consideration the material characteristics ideal to support the lifecycle for this energy storage device. Start-up time for compressed air energy storage systems is also another critical area for research activities. This is very important in order for compressed air energy storage systems to be able to compete with existing energy storage devices. The cost of air reservoirs must also be reduced. For adiabatic compressed air energy storage systems, it is recommended that heat storage devices be integrated into the storage system to improve the power and energy densities for the entire system. Motor generators can also be added to turbo machines to enhance performance as well. Battery storage devices are presently being used in both off-grid and portable applications, but for compressed air energy storage systems to replace battery, there will need to be a reduction in the overall cost of the system. Modularity of compressed air energy storage systems is another key issue that needs further investigation in other to make them ideal for various applications.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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